AN ASSESSMENT OF PEDESTRIAN INFRASTRUCTURE QUALITY AND THE EFFECT ON TRAVEL TIME AND MOBILITY FOR USERS WITH PHYSICAL LIMITATIONS

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AN ASSESSMENT OF PEDESTRIAN INFRASTRUCTURE QUALITY AND THE EFFECT ON TRAVEL TIME AND MOBILITY FOR USERS WITH PHYSICAL LIMITATIONS

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LIST OF SYMBOLS AND ABBREVIATIONS

AAPD	American Association of People with Disabilities
ADA	Americans with Disabilities Act
ADAAG	Americans with Disabilities Act Accessibility Guidelines
ESRI	Environmental Systems Research Institute
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPS	Global Positioning System
MAGUS	Modelling Access with GIS in Urban Systems
MARTA	Metropolitan Atlanta Rapid Transit Authority
NACTO	National Association of City Transportation Officials
NHTS	National Household Travel Survey
OD	Origin-Destination
UN	United Nations
USAB	United States Access Board

SUMMARY

The purpose of this thesis is to analyze the potential effect that pedestrian infrastructure ADA compliance issues may have on persons with disabilities or physical limitations. Pedestrian infrastructure was inventoried and compliance issues were assessed in Midtown, Atlanta using the Sidewalk Sentry and Sidewalk Scout applications. Pedestrian infrastructure inspection data for the Midtown network were compared to ADA design standards and sidewalk sections were assigned an overall compliance value. Using the ADA compliance issues, travel-time impedance values were assigned to each sidewalk and ramp element that comprise the pedestrian infrastructure in Midtown. Five sets of travel time impedance values were assigned to the infrastructure, where travel time impedance values were assigned using historical rankings of the most problematic sidewalk barriers according to disabled persons. Using Network Analyst in ArcGIS, the shortest paths were calculated between 500 random origins and destinations before and after assigning issues a travel time impedance value. The results of the analysis indicate that while current pedestrian infrastructure may meet the needs of able-bodied users, the infrastructure limits the mobility of persons with disabilities. The findings show that pedestrian infrastructure that is in disrepair increases the average travel time and length of travel for persons with disabilities. Noncompliant pedestrian infrastructure also prohibits disabled persons from making approximately one fourth of the trips that an able-bodied person can make in Midtown, Atlanta.

CHAPTER 1. INTRODUCTION

A truly accessible pedestrian environment is characterized by sidewalk presence and proximity to goods and services and also by well-maintained sidewalks, curb ramps, and curb cuts that are designed to ensure the safety and comfort of pedestrians of all abilities. Sidewalk presence, coupled with sidewalk quality, are important factors when considering the ease of movement by users along the system. While individuals with full mobility are usually able to overcome problems in the pedestrian network, it is significantly more difficult for users with mobility impairments to traverse the same infrastructure. The condition of community walking environments can be evaluated using tools that take into consideration proximity to amenities, block length, intersection density, and population density.

This thesis uses sidewalk, curb ramp, and curb cut quality data to assess the state of pedestrian infrastructure in Midtown, Atlanta. The assessment specifically focuses on how the design and condition of the sidewalks in Midtown, Atlanta effect the movement of people with disabilities or mobility impairments. The travel time between random origins and destinations in Midtown are calculated using Dijkstra's shortest-path algorithm, in the ArcGIS Network Analyst tool. Network Analyst is used to calculate the travel time between origins and destinations before and after adding sidewalk travel-time impedance values to the Midtown network. Infrastructure quality data such as sidewalk roughness, curb ramp problems, curb cut problems, and sidewalk compliance issues are assigned impedance values to assess the potential impacts these issues have on user movement throughout the sidewalk network. Midtown, Atlanta is used as a case study to show the effects sidewalk quality issues have on persons with physical limitations; however, this analysis can be reproduced in any community that obtains pedestrian infrastructure condition data. This analysis also can be employed by communities to maintain their sidewalks and prioritize sidewalk repairs by identifying problem areas that limit mobility for users of all abilities.

CHAPTER 2. LITERATURE REVIEW

2.1 Benefits of Walking and Pedestrian Infrastructure

2.1.1 Walking and Public Health

Research suggests that mental and physical health problems in individuals can be exacerbated or improved by the built environment in which they are surrounded by on a daily basis (Srinivasan, 2003). The built environment can be characterized as work, home, parks, roads, and practically any other unnatural space that is modified by people (Health Canada, 2003). Transportation is one of the main components of the built environment and can positively or negatively impact public health. Isolated communities that heavily depend on automobiles for their primary mode of travel are prominent in the United States. Isolated communities often see a higher proportion of their residents leading a sedentary lifestyle, which are correlated with high rates of obesity and diminished public health (Srinivasan, 2003).

Issues with the built environment, specifically transportation infrastructure, can also be seen in communities that are not isolated. Over the past sixty years, populations have been moving from rural to urban areas (Boyd, 2017). United Nations estimates show that approximately eighty-two percent of North Americans live in urban areas with heavy concentrations in large to mid-sized cities. (Boyd, 2017). Despite the rapid movement of people to dense, connected urban areas, the percentage of people who walk to work in the United States has decreased dramatically since 1960 (Boyd, 2017).

Not only has the percentage of commuters that walk to work decreased, but so has the number of children who walk to school. Currently, only ten percent of school-aged children walk to school- a forty percent reduction since 1980 (Killingsworth, 2001). Research indicates that inadequate urban planning coupled with a lack of pedestrian infrastructure has contributed to fewer walk trips, an increasingly inactive lifestyle, and higher obesity rates in children and adults (Goran, 2001).

The auto-centric nature of communities in America perpetuates sedentary lifestyles and the lack of physical activity undergone by Americans may be considered a public health issue. The preference for driving over walking has been rooted in the minds of Americans, even when walking trips are possible (Frumkin, 2004). Studies show that the average person is willing to travel less than one fourth of a mile on foot, and in some instances as little as 400 feet to reach destinations (Frumkin, 2004). Promoting walking as a form of transportation, however, is one way to get individuals moving and ultimately improve the overall health of communities. As little as thirty minutes of daily physical movement can decrease risks of ‘cardiovascular disease, breast cancer, colon cancer, stroke, type II diabetes, and even reduce the risk of premature death for individuals’ (Veisten, 1991). Walking also promotes healthy aging by improving physical health for older populations. Physical activity, such as walking, can postpone disorders that are worrisome for aging adults and also extend the number of years of independent and functional living. (US Department of Health and Human Services, 2015).

2.1.2 Walking and the Environment

Not only does walking have the potential to improve the overall quality of life, walking also provides environmental benefits as well. Increased walking can mean fewer vehicles on the road, lower emissions and energy use, reduced traffic noise, and fewer traffic related injuries and deaths (Diabetes Australia, 2017). According to the National Household Travel Survey, twenty eight percent of trips made are one mile or less and forty percent of trips are two miles or less (NHTS, 2010). Of those one-mile trips, thirty five percent are walked and of those two mile trips, twenty six percent are walked (NHTS, 2010).

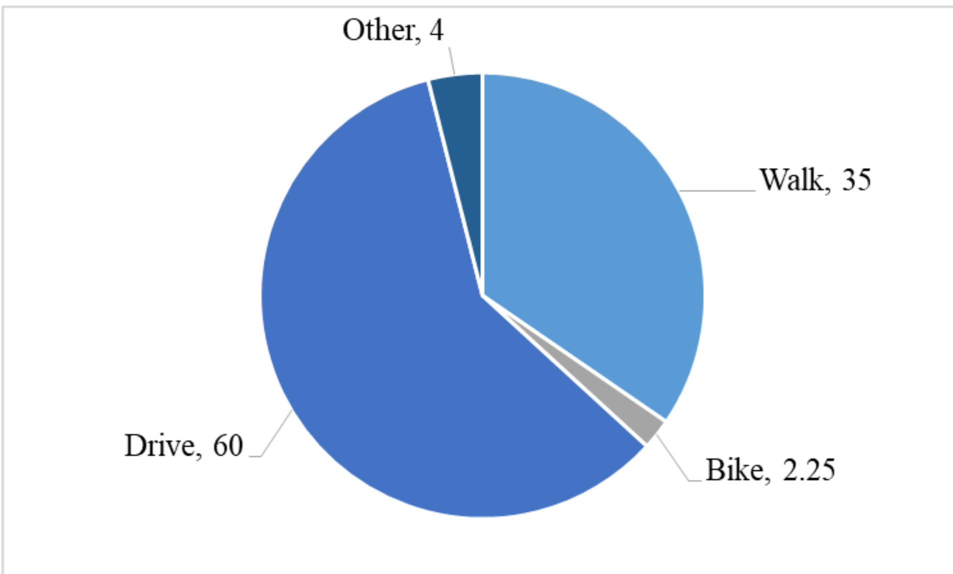

Figure 1. Mode Split of Trips Less than One Mile (NHTS, 2010)

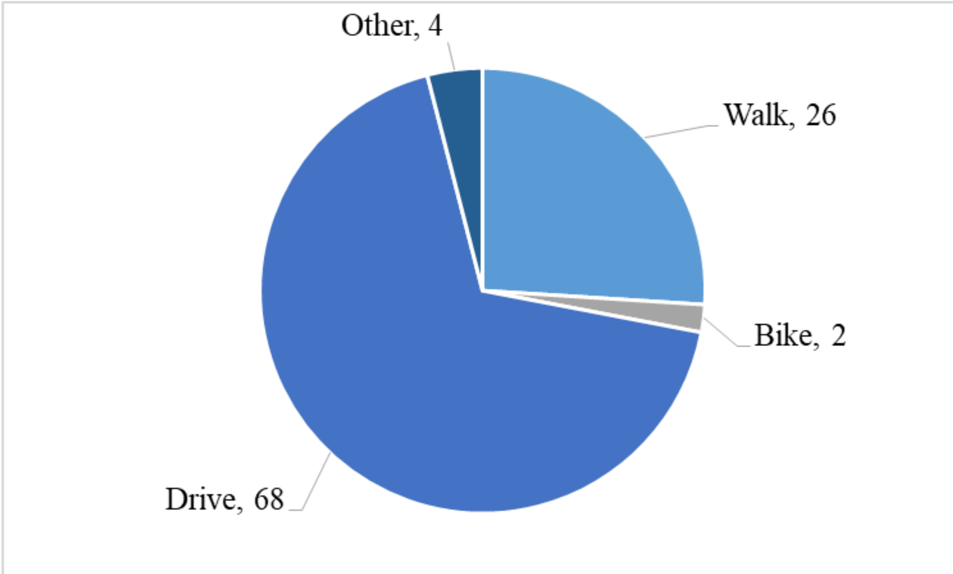

Figure 2. Mode Split of Trips less than Two Miles (NHTS, 2010)

Because nearly half of the nation's trips are under two miles, it is feasible for some of these trips that are dominated by driving, to be transformed into walking trips. Vehicle trips with the ability to be transformed into walking trips consist of ones that are within a thirty-minute walkable distance to goods and services and where walking is a safe and comfortable alternative. For trips under two miles, or less than 30 minutes from origin to destination, walking is considered a feasible alternative and can lead to reduced pollution from the elimination of a vehicle travelling such a short distance (World Health Organization, 2015).

Reducing the number of vehicle miles traveled can reduce vehicle emissions, energy use, and greenhouse gas emissions, as well as noise pollution. Studies show that extended periods of noise exposure can lead to 'annoyance, sleep disruption, daytime drowsiness, and also impairs the cognitive performance in children' (Basner, 2014). Along with this, noise pollution can increase the risk of hypertension and cardiovascular disease in adults (Basner, 2014). Reducing noise pollution can provide a more comfortable and healthier living environment for residents of a community.

2.1.3 Walking and Economics

Transportation is the second largest household financial burden in the United States (AmericaWalks, 2017). In fact, the average annual cost of vehicle upkeep in the United States is estimated to be around $9,000 per household (AAA, 2012). Each additional car in a household subtracts around $150,000 from that household’s potential mortgage capacity. Reducing the number of cars in each household, on the other hand, increases each household’s mortgage capacity by the same amount (Freedman, 2008). Substituting walking trips for vehicle trips in sufficient number has the potential to reduce the financial burden on households when they can reduce vehicle ownership and reduce annual costs associated with vehicle insurance, fuel, and maintenance. The reliance on automobiles stems from the fact that they are often the most convenient way to travel from origin to destination, especially when considering the time it takes to travel from place to place. Walking as an alternative to driving a vehicle is most likely to occur in dense urban landscapes, with plenty of desirable origins and destinations within walking distance. Walking only has the potential to become a high utility mode when land use supports walking as a viable mode of transportation.

2.1.4 Walking and the Role of City Planners and Transportation Professionals

Individuals are less likely to walk when the pedestrian infrastructure is inadequate (Veisten, 1991), so it is vital that sidewalks and ramps be of high quality and planned in a thoughtful manner. Transportation engineers and urban planners can improve the design of communities and construct infrastructure that promotes active forms of transportation, such as walking. Providing connected, high-quality infrastructure, as well as developing dense, mixed-use communities can promote walking in these communities. According to the U.S. Surgeon General, planners should include 'well-maintained sidewalks, pedestrian friendly streets, access to public transit, adequate lighting, and desirable destinations that are close to home' so that 'everyone [can] have access to spaces and places that make it safe and easy for us to walk or wheelchair roll (US Department of Health and Human Services, 2015). Urban planners and transportation professionals have the ability to encourage walking in communities by implementing the following aspects into the design of cities (Losa, 2014):

- Mixed Land Use: High-density and mixed-use development helps minimize the number and length of vehicle trips and increases the number of short trips that can be made by walking
- Presence of Infrastructure: Provision of adequate pedestrian infrastructure and smart sidewalk design discourages automobile use and encourages walking
- Sidewalk Maintenance: High-quality pedestrian infrastructure encourages walking as a form of transportation, ensures that the disability community can access the infrastructure (an equity argument), and improves pedestrian safety

2.2 Mobility, Accessibility, and Walkability

The following section explores mobility, accessibility, and walkability. Mobility, accessibility, and walkability are important when taking into consideration pedestrian infrastructure and walking as a mode choice. A pedestrian network's utility is derived from its access to goods and services, comfort, safety, and the facilitation of movement along the network.

2.2.1 Mobility

Mobility is the ease in which movement can be made. On a large scale, mobility often refers to movement from community to community or even region to region, which is supported by roadway networks and long-distance transit services. Traffic engineers often relate the concept of mobility to person-miles of travel or person-trips on the basis that ease of mobility translates into more travel activity (Litman, 2017). Furthermore, that increase in travel activity is generally assumed to provide positive benefits to society as a whole (Litman, 2017).

With respect to travel by walking, mobility does not always translate to greater travel distances. Pedestrian travel activity is constrained by both time and distance (effort). For walking, therefore, mobility really does need to remain focused on the ease of movement through the pedestrian network. Factors that decrease the mobility, or the ease of movement through a sidewalk network, include a variety of physical barriers that add stress or travel time or effort to a trip.

Physical sidewalk and pedestrian infrastructure issues are of particular importance to wheelchair users and the visually impaired, because they may experience more trouble when trying to overcome barriers, such as uneven surfaces or lack of curb ramps, along a sidewalk network. Therefore, mobility along a sidewalk network can be thought of as the ease of movement for users of all abilities. Mobility along a sidewalk network is enhanced when the surface is well-maintained and no physical obstacles are present.

2.2.2 Accessibility

Accessibility is an assessment of the ability of transportation users to reach activities, businesses, goods, and services along the transportation network (see University of Minnesota, 2011). According to the Victoria Transport Policy Institute, accessibility is the most important goal of the most transportation systems, allowing people and businesses to connect with goods and services (Litman, 2011).

Accessibility and mobility go hand in hand. For people to be able to access a good or service, they need to be able to move easily throughout the network. Accessibility is also dependent on land-use patterns and the location of goods, services, and activities relative to each other and to residential and work locations. Accessibility can be enhanced through mixed-use developments, multi-modal transportation options, and walkable communities, which can reduce the time it takes to travel from origins to destinations of interest or may eliminate the need for an automobile (Litman, 2011). Accessibility does not necessarily put an emphasis on the fastest mode that can get a user from origin to destination, but can emphasize a myriad of modes (Litman, 2011). Travelers value these modes according to the extent to which the modes meet their travel needs and constraints.

Shorter trips and slower modes of transportation, such as walking, can compete with faster modes when they provide adequate access to services (Litman, 2011). In terms of pedestrian infrastructure, accessibility can be thought of as the ability to reach important activities, goods, and services in a reasonable walking time. A sidewalk network that does not take users to desirable destinations does not support accessibility, while a complete sidewalk network in a dense, mixed-use environment is much more likely to reach numerous locations of interest.

Walking accessibility is also important with respect to transit use. The first and last mile connections to transit options in communities often involve walking. A sidewalk network can be considered even more accessible when it connects to transportation options that increase the number of goods and services a user can access with a reasonable expenditure of time, money, and effort.

2.2.3 Mobility vs. Accessibility

According to FHWA, movement barriers within the pedestrian environment include curbs, steep slopes, obstacles, and sidewalk widths that are too narrow (FHWA, 2004). Movement barriers can drastically decrease the mobility of a user on a pedestrian network by eliminating the possibility of reaching a destination, by increasing the time it takes to move from point to point, or by decreasing the ease of travel along the network. This is especially true for users with mobility impairments who rely on wheelchairs, scooters, or walkers to travel. The travel time added when faced with a movement barrier can drastically decrease the number of amenities a mobility-impaired user can access in a reasonable time. Decreasing the mobility of a user along a sidewalk network, or how far a user can travel in a given time period, reduces the number of activities that can be reached in that time period, and therefore reduces walking accessibility. However, a more comprehensive and holistic evaluation of mobility is necessary when taking into consideration alternative modes of travel, because the quality of the network also plays a large role in how far a user can travel and what destinations they can reach within a certain time interval.

2.2.4 Walkability

Walkability is a term used to describe the physical environment in which the action of walking occurs (Glanz, 2011). The built environment that is described when talking about walkability consists of the space shaped by streetscapes, streets, and buildings that surround the walking area. A walkable community is typically characterized by more than just the presence of pedestrian infrastructure. Rather, a walkable community is characterized by having rich pedestrian-centered infrastructure that includes 'wide high-quality sidewalks, active street frontages, traffic calming measures, street trees and vegetated buffers, marked and signalized crossings, benches, way-finding signage, and pedestrian lighting.' (Al-Hagla, 2009). The following features are generally believed to improve the walking environment and walkability:

-Street Lights

-Street Trees

-Wide Sidewalks

-Traffic Calming Measures

-Buffers

-Marked Crossings

-Signalized Crossings

-Wayfinding

-Benches

-Frontage Zone

The figures below show what some might consider an example of an ideal pedestrian environment and an ideal crossing environment. Figure 3 shows a wide sidewalk with adequate lighting, street trees, buffers, benches, traffic calming measures, and a frontage zone. Figure 4 shows a marked crossing that contains curb ramps that are adequate for persons with disabilities. The crossing in Figure 4 contains traffic calming measures, such as extended curbs, that increase the visibility of pedestrians and decrease the time it takes for pedestrians to cross the intersection. Figures 3 and 4 demonstrate ideal pedestrian infrastructure that provides safe, comfortable, and appropriate features for users.

Figure 3. Example of a Walkable Pedestrian Environment (NACTO, 2013)

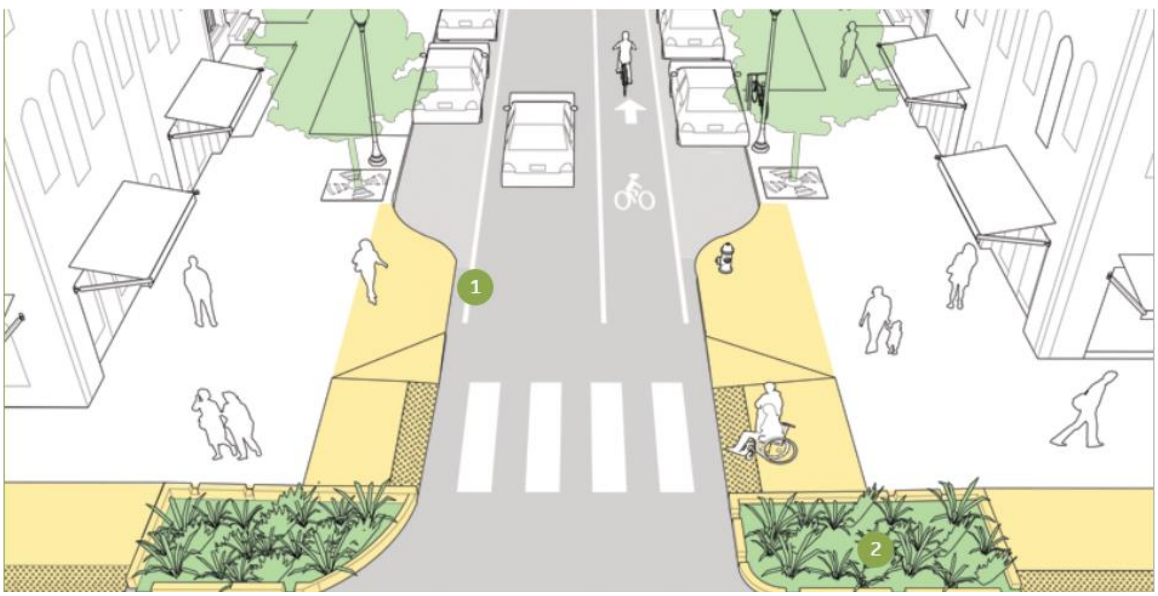

Figure 4. Example of a Safe Pedestrian Crossing (NACTO, 2013)

Even if desirable services and goods are within walking distance of an origin, people are less likely to travel by foot if the sidewalks are in poor condition or if the environment feels unpleasant or unsafe to the user (Opticos Design, 2015). Such perceived travel costs can affect mode choice. Traffic calming interventions can make sidewalk users feel safer by slowing down the speed of adjacent traffic or by shortening the distance a pedestrian has to travel when crossing the road, increasing the likelihood that they will walk between activities and therefore increasing walking accessibility (they are now willing to visit more places). Figure 5 illustrates examples of traffic calming measures that can improve walkability:

Curb Extensions	
Chicane	
Vertical Speed Control	
Lane Narrowing	

Figure 5. Examples of Traffic Calming Measures (NACTO, 2015)

2.3 Transportation and the Disability Community

Finding viable transportation options can potentially be a huge struggle for people with disabilities, especially considering the fact that the United States places a huge emphasis on cars as its main form of transportation. Many people with disabilities, who are unable to operate a vehicle on their own, rely heavily on public transportation. However, affordable public transportation options that connect the disabled with vital goods and services do not always exist, or if they do, they are inadequate. In fact, of the 'nearly 2 million people with disabilities who never leave their homes, 560,000 never leave home because of transportation difficulties' (AAPD, 2009). Not only do bus services, paratransit services, and train services need to be accessible for people of all abilities, but an appropriate path-of-travel to these transportation options must also be provided. Public transportation is only useful if users of all abilities can actually move safely along their sidewalks to reach the transportation option. Oftentimes, barriers such as missing curb ramps and sidewalk obstructions can impede the ability of a disabled individual to reach a transportation service. Problems such as this are often considered inequitable, because they limit the mobility and therefore the accessibility of disabled users far more than they do able-bodied users.

2.4 Walk Score

The Walk Score is a tool that has been developed to quantify the accessibility of a certain address or location (Walk Score, 2011). A Walk Score is calculated by first mapping out the number of amenities within walking distance to a certain location and dividing them into nine separate categories (Walk Score, 2011). The distance to a location, coupled with amenity counts and weights, contribute in the determination of the base score of a particular location of interest which is then normalized on a scale from one to one hundred (Walk Score, 2011). The score of a particular location can be weighted down if the intersection density is low or if lengthy blocks are present (Walk Score, 2011). According to Walk Score, the amenity weights 'were chosen based on our interpretation of current walkability research' (Walk Score, 2011). The developers of Walk Score go on to support their methodology by stating that amenities like grocery stores, banks, schools, restaurants, and retail increase the number of walking trips made in a certain area (Lee, 2006). Amenity categories are weighted based on whether they are of high importance to walk trips, medium importance to walk trips, or low importance to walk trips (Walk Score, 2011).

A distance decay function is used to analyze what proportion of a full score each category will be allocated based on the distance between the service and the position of interest (Walk Score, 2011). Because the ideal range of distance between an origin and an amenity is considered to be one fourth of a mile or less for walking trips, a full score is assigned to amenities within this distance from the origin and decline the further away an amenity gets from a destination (Walk Score, 2011). Any amenities over one and a half miles away from the origin are not included when calculating the overall Walk Score due to the fact that 1.5 miles is considered the 'maximum sensible distance the average person is willing to walk from origin to destination' (Walk Score, 2011). Walk Score uses the standard walking speed of 3 miles per hour to calculate walking time (Walk Score, 2011).

According to the definitions of accessibility, mobility, and walkability discussed previously, calculations made using the Walk Score algorithm are assessing the accessibility of an address. This is evident given the heavy emphasis Walk Score places on the number of amenities within a walking distance to the address of interest. While there is some emphasis on connectivity and walkability, the backbone of the Walk Score revolves around the number of amenities within one-fourth to one and a half miles away from the initial origin. The methodology used by Walk Score is a valid way to quantify the accessibility of a location, however the Walk Score methodology does not address pedestrian mobility nor the walkability of pedestrian infrastructure. When Walk Score assigns values to a certain location, the rating may not be relevant for a disabled individual if the sidewalk network is in disrepair and the individual cannot reach the destinations. A more accurate measurement of the mobility of an area would take into consideration the quality of the pedestrian infrastructure along the path of travel and thus the abilities of all users.

2.5 Americans with Disabilities Act

The Americans with Disabilities Act (ADA) was passed by Congress in 1990 and sets policy guidance to protect the rights of persons with disabilities (ADA National Network, 2017). The ADA prohibits discrimination in employment, public services, and telecommunications (ADA National Network, 2017). The ADA also addresses the basic needs of persons with disabilities and limited mobility and ensures that people of all abilities have the same rights and opportunities as all other American citizens (ADA National Network, 2017). The rights that are protected by the ADA include employment opportunities, purchasing goods and services, and participation in local government, along with many others (ADA National Network, 2017). The ADA also sets standards for public infrastructure and transportation, ensuring that disabled individuals are able to access public goods and other amenities in an equal manner (ADA National Network, 2017).

The ADA not only applies to basic rights but also provides standards for private and public transportation services which are overseen by the United States Department of Transportation (ADA National Network, 2017). The ADA sets architectural, paratransit, as well as facility design standards for transportation entities (USAB, 2002). These standards address a variety of transportation issues ranging from the way information is displayed and communicated on transportation vehicles, to the design of transit facilities and bus stops (ADA National Network, 2017).

In 2002, the first ADA Accessibility Guidelines addressing the accessibility of pedestrian infrastructure was published by the United States Access Board, making sidewalks a significant topic of conversation in terms of ADA accessibility and equality for persons of all abilities. (USAB, 2002). The ADA then published its Standards for Accessible Design in 2010 which aimed to set requirements 'for newly designed and constructed state and local government facilities, public accommodations, and commercial facilities to be readily accessible to and usable by individuals with disabilities' (Department of Justice, 2010). These design standards apply to sidewalks and other related pedestrian infrastructure, such as curb ramps and curb cuts, that are considered part of the public path of travel to goods, services, and transportation options (Department of Justice, 2010). Pedestrian infrastructure such as sidewalks, curb ramps, pedestrian signals, crosswalks, and driveway crossings all have specific design requirements that must be met to promote equal access for all individuals. The tables below show the specific standards for sidewalks, curb ramps, and curb cuts that are set by the ADAAG.

Table 1. ADA Standards for Sidewalk Design

Sidewalk Attribute	ADAAG Requirement
Sidewalk Width	Minimum 36 inches
Cross Slope	Maximum 2%
Running Slope	Maximum 5%
Changes in Level	Vertical displacements up to 0.25” are allowed Vertical displacements from 0.25”-0.5 inches must be beveled to a slope not exceeding 1:2 Vertical displacements greater than 0.5 inches must be smoothed to not exceed a slope of 8.33%
Pavement Material	Surface must be firm, stable, and slip resistant
Obstructions	No obstructions may be present within the pedestrian route
Vertical Clearance	Minimum 80 inches

Table 2. ADA Standards for Ramp Design

Ramp Attribute	ADAAG Requirement
Ramp Width	Minimum 36 inches
Passing Area Above Ramp Landing	36 inches behind ramp
Running Slope	Maximum 8.33%
Cross Slope	Maximum 2%
Gutter Slope	Maximum 5% from street to bottom of ramp
Changes in Level	Vertical displacements up to 0.25" are allowed Vertical displacements from 0.25"-0.5 inches must be beveled to a slope not exceeding 1:2 Vertical displacements greater than 0.5 inches must be smoothed to not exceed a slope of 5%
Ramp Pavement	Surface must be 'firm', 'stable', and 'slip resistant'
Obstructions	No obstructions may be present
Vertical Clearance	Minimum 80 inches
Detectable Warning Surface	Detectable warning surface must be present
Flare Slopes	Maximum 10%

Table 3. ADA Standards for Curb Cut Design

Curb Cut Attribute	ADAAG Requirement
Cross Slope	Maximum 2%
Passing Width	Minimum 36 inches
Left and Right Flare Slopes	Maximum 10%

The results of a 2002 court ruling (Shoup, 2010) and the subsequent publishing of ADA's Standards for Accessible Design, require cities to take responsibility for the condition of their sidewalks. Cities are required to create ADA transition plans (e.g., Mudrinich, et al., 2015) to assess the accessibility of their sidewalks for all users of the system. ADA transition plans are a self-evaluation tool that assists cities in creating benchmarks for sidewalk and curb ramp maintenance and repairs (United States Department of Justice, 2008).

Cities struggle to attain and maintain their pedestrian infrastructure to the standards derived under the ADA. Many cities throughout the United States still have sidewalks, curb ramps, and curb cuts that are inaccessible to people with physical limitations and mobility impairments. Broken sidewalks, steep sidewalks and curb cuts, and missing curb ramps are a few of the common problems that disabled persons face when trying to navigate from origin to destination. Pedestrian infrastructure problems such as these are dangerous for disabled users and create a transportation equity concern. Nevertheless, these infrastructure problems are commonly put on the back burner by cities and municipalities due to fiscal constraints and inadequate sidewalk maintenance strategies. Most pedestrian infrastructure barriers such as these go unnoticed by able-bodied users, but impede the ability of disabled persons to access goods and services that should be readily available to them. Sidewalk, ramp, and curb cut compliance issues increase the travel time and decrease the mobility for users with physical limitations or disabilities.

In the United States, sidewalk ADA compliance is typically driven by lawsuits and litigation. For example, a class action lawsuit filed under ADA claimed that the City of Los Angeles did not maintain their sidewalks in a way that is 'usable by class members who rely on wheelchairs, scooters, and other assistive devices to get around' (Goodyear, 2015). The lawsuit resulted in an obligation on the part of the City of Los Angeles to allocate $1.4 billion dollars to sidewalk maintenance and repair over the next thirty years (Goodyear, 2015). The City of Seattle was sued in 2015 because its curb ramps failed to meet the standards set forth by ADA or did not exist all together in some areas (Gutman, 2017). A lawsuit filed in Oregon for issues relating to sidewalk and curb ramp compliance, yielded changes in state policies and financial obligations as well. The Oregon lawsuit resulted in the state agreeing to allocate $23 million dollars to sidewalk and curb ramp repairs (Gutman, 2017). Chicago experienced the same type of ADA lawsuit over a decade ago, resulting in the city pledging to spend $50 million in repairs over the span of five years (Gutman, 2017). ADA lawsuits involving pedestrian infrastructure, such as the cases mentioned above, have become commonplace in the United States. Settlements involving sidewalk repair have been reached with over 240 counties, cities, and local governments through the Project Civil Access program and the United States Department of Justice (Gutman, 2017).

Despite the efforts of cities to ensure that their pedestrian infrastructure meets ADA standards, serious budget and maintenance constraints still exist. For instance, the city of Atlanta estimated that 395 miles of sidewalks (18%) and 216 miles (10%) of curbs were in disrepair in 2010 (City of Atlanta Department of Public Works, 2010). These values represent a large proportion of the city's 2,158 miles of sidewalk. The city of Atlanta estimates that the deteriorated sidewalks and curb ramps would cost approximately $152 million to repair (City of Atlanta Department of Public Works, 2010). The cost of repair for Atlanta's sidewalks and curbs far exceeds Atlanta's 2010 budget of $420,000 per year (City of Atlanta Department of Public Works, 2010). Los Angeles estimates that 4,600 (43%) of the city's 10,750 miles of sidewalk are in need of repair (Shoup, 2010). The estimate for repairing the deteriorated sidewalks would cost Los Angeles approximately $1.2 billon (Shoup, 2010). While the city has dedicated enough funds to potentially fix its ADA compliance issues, this process could take a full 30 years to complete. Los Angeles and Atlanta are no exception; serious backlogs in sidewalk maintenance and repairs are common in the majority of cities throughout the United States. Even with millions of dollars allocated to sidewalk repair from ADA litigation and municipal budgeting, the likelihood of all sidewalks and curb ramps being repaired in a timely manner is unlikely. Therefore, prioritizing sidewalk repairs to areas of serious risk first is important.

While ensuring that all pedestrian infrastructure meets ADA requirements is imperative, cities may need assistance in prioritizing sidewalk repair projects over the lifespan of planned maintenance efforts. Sidewalk condition data can be collected and compared against ADA standards (i.e., an official benchmark). Such comparisons can assist cities in prioritizing where sidewalk, curb cut, and curb ramp funds should be allocated. The assessment of sidewalk problems that decrease the mobility of users (i.e., decrease the distance that users can travel in a certain period of time) or are completely impassable to some or all users can help cities decide which projects should be constructed immediately given that sidewalk funding is typically limited and long project timelines are common.

2.6 Previous Studies on the Effect of Sidewalk Quality and Mobility

There are many sidewalk quality issues that affect the experience and overall travel time for a person with a mobility impairment. Quality issues can range from sidewalks with displacements exceeding 0.25 inches to completely missing curb ramps. Sidewalk compliance issues that do not meet ADA standards have the potential to prevent persons from traveling along the network, can decrease the length in which that person can travel, and can increase the time it takes to get from point A to point B. A literature review of sidewalk quality issues that have the strongest effect on persons in wheelchairs or with mobility aids has been conducted and the methodology is examined in the following section. The table below shows sidewalk problems that have the largest effect on persons traveling along a sidewalk network. Table 4 summarizes the findings of four separate research efforts and provides an overview of the most important sidewalk features that limit mobility, as noted by wheelchair users themselves. The table below represents sidewalk attributes that impede travel the most from the perspective of wheelchair users.

Table 4. Review of Attributes that Impede Wheelchair Users Travel

Sidewalk Problems that Impede Travel (Beate, 2006)	Sidewalk Problems that Impede Travel (Sobek , 2006)	Sidewalk Problems that Impede Travel (Karimanzira, 2006)	Sidewalk Problems that Impede Travel (Kasemsuppakom, 2009)
Slope	Sidewalk Width	Slope	Slope
Narrow Width	Steps	Sidewalk Width	Sidewalk Width
Fixed Street Furniture	Segment Length	Steps	Steps
Steps	Ramp Slope	Segment Length	Segment Length
Segment Length	Ramp Width	Surface Quality	Surface Type
Surface Type	Ramp Passing Width	Road Traffic Control	Cracks/Potholes
Surface Quality	Curb Problems	Road Traffic Density	Manhole Covers
Manhole Covers	Parking Width	Road Traffic Type	Uneven Surfaces
Ramp Slope			Sidewalk Traffic

Source: Kasemsuppakom, 2009

Kasemsuppakom (2009) attributed a sidewalk quality value to each portion of their sidewalk network using a ‘matrix of paired comparison judgements.’ Each interviewee was asked to check a box that rated each sidewalk quality problem versus every other sidewalk quality problem (Kasemsuppakorn, 2009). An example of the survey performed by Kasemsuppakom can be seen in Table 5. Each survey respondent compared each sidewalk problem identified with all of the other sidewalk problems identified. If the two problems were of equal importance, users selected No Difference. For problems that were different, users indicated which problem was more important and the relative difference in importance by selecting a box closer to the more important problem.

Table 5. Example of Survey Comparing Sidewalk Problems

Which paramter prevents your mobility the most?										
Extremely Different More Important ←					No Difference					→ Extremely Different More Important
Slope					**X**					Steps
Slope			**X**							Width
Slope		**X**								Distance
Slope						**X**				Surface
Slope				**X**						Traffic
Steps			**X**							Width
Steps	**X**									Distance
Steps			**X**							Surface
Steps		**X**								Traffic
Width		**X**								Distance
Width									**X**	Surface
Width					**X**					Traffic
Distance									**X**	Surface
Distance			**X**							Traffic
Surface	**X**									Traffic

Source: Kasemsuppakom, 2009

Each problem was set to a numeric scale from one to nine, where one meant equal (no difference) and nine meant extremely more important (Kasemsuppakom, 2009). From the responses, Kasemsuppakom, (2009) created a comparison matrix (an example can be seen in Table 6).

Table 6. Comparison Matrix of Pedestrian Infrastructure Problems

	Slope	Steps	Width	Distance	Surface	Traffic
Slope	1	1	5	7	1/3	3
Steps	1	1	5	9	5	7
Width	1/5	1/5	1	7	1/9	1
Distance	1/7	1/9	1/7	1	1/9	5
Surface	3	1/5	9	9	1	9
Traffic	1/3	1/7	1	1/5	1/9	1

Source: Kasemsuppakom, 2009

A weight for each sidewalk issue was then calculated by taking each individual entry and dividing it by the sum of the column, thus assigning each sidewalk compliance issue a weighted value from zero to one (Kasemsuppakom, 2009) and the final calculated weights of each sidewalk compliance issue can be seen in Table 7.

Table 7. Final Weightings of Sidewalk Problems.

Problem	Weight
Slope	0.179
Steps	0.331
Width	0.068
Distance	0.050
Surface	0.296
Traffic	0.075
Sum	1.000

Source: Kasemsuppakorn, 2009

The methodology shown above was developed by Kasemsuppakorn to assign an impedance value to each sidewalk segment according to perceptions of wheelchair users. Kasemsuppakorn (2009) then assigned a total impedance value for segments along the sidewalk network to identify severe problem areas for persons with mobility impairments.

Other surveys of wheelchair users have been performed to assess the most common barriers that the users have to overcome on a day-to-day basis. A longitudinal survey created by Meyers was performed over twenty-eight days with twenty-eight participating wheelchair users (Meyers, 2002). Each survey respondent was asked to complete a daily phone survey relating to their mobility and travel experiences (Meyers, 2002). In these daily surveys, ‘respondents were asked to identify the destinations they had reached or were unable to reach, the barriers they had overcome, and those they had not overcome, and facilitators that they had encountered’ (Meyers, 2002). The most successful reached destinations were civic destinations (Meyers, 2002). The most common barrier for wheelchair users was the presence of high curbs with no curb ramp present (Meyers, 2002). With respect to sidewalk features, the most common barriers overcome were narrow sidewalks, no ramps or ramps too steep, no curb cuts, blocked curb cuts, poor travel surfaces, and obstructed sidewalks (Meyers, 2002). Some insurmountable barriers cited by Meyers included a lack of available ramps or ramps that were too steep or had high curbs (Meyers et al, 2002).

The survey indicates that there may be significant variability in the physical abilities of different wheelchair users. Some of the barriers that some of the users were able to overcome were never listed as barriers that they were unable to overcome. Some pedestrian infrastructure barriers were listed in the able to overcome and the not able to overcome categories for varying users. However, steep ramps and lack of ramps appeared in both categories. Hence, the range of physical ability for persons using wheelchairs or mobility aids may be something to consider further.

Another survey, administered in Northamptonshire, England, consisted of answers from 102 wheelchair users in the area on local sidewalk barriers (Matthews, 2003). Along with this survey, wheelchair users were asked to participate in focus groups and site visits throughout Northamptonshire to assess sidewalk quality and potential mobility barriers (Matthews, 2003). The most common problems that impeded the movement of wheelchair users consisted of the surface and positioning of curb ramps, lack of curb ramps, narrowness of sidewalks, uneven surfaces, misaligned curb ramp and gutters, obstructions in the path, and the discomfort caused by cobblestone pathway (Matthews, 2003). The most common curb ramp problems stated by wheelchair users were steep slopes, small passing widths, and uneven surfaces (Matthews, 2003). The curb ramp problems that affected wheelchair users the most were surface problems (Matthews, 2003). A table from Matthews' study consisting of the most cited barriers and relative impedance values for wheelchair users can be seen in Table 8.

Table 8. Most Frequently Cited Barriers as Determined by Wheelchair Users

Barrier (Mean Rank Order)	Self-propelled User Scores	Motorized User Scores
Steps	1.17	1.0
High Curbs (No Curb Ramp)	2.25	2.00
Gravel Surfaces	3.75	4.00
Deep Gutters	3.83	6.00
Lack of Dropped Curbs	5.00	4.00
Steep Gradients	6.00	7.50
Narrow Pavements	6.83	8.00
Adverse Cambers	8.08	7.50
Poor Maintenance	8.41	7.00
Cobbled Surfaces	9.67	8.00

Source: Matthews, 2003

In the table above, sidewalk problems with the lowest score represent the highest impedance (Matthews, 2003). From this survey, the most intense problems faced by wheelchair users are stairs and high curbs with no curb ramps (Matthews, 2003). The fact that these sidewalk problems returned the highest impedance values seems logical, considering that it may be extremely dangerous or impossible to traverse these specific barriers. It is likely that wheelchair users may have to turn around and find an alternative route when faced with these two barriers. Gravel surfaces cause discomfort for wheelchair users, increase the time it takes to traverse a network, and can result in a fall due to uneven surfaces. Narrow pavements potentially have similar effects on persons using mobility aids. Lack of space for a wheelchair could result in the user having to either travel into the street, travel on grass or dirt near the narrow sidewalk, or turn around.

Most travel routing platforms and navigation applications for pedestrians simply provide the shortest route, and do not take into consideration the route condition as a whole or the difficulty a disabled person may have traversing the route. However, a network routing system that displays up to date information on sidewalk quality issues that affect disabled persons is necessary to provide accurate directions from origin to destination. One such tool is the Modeling Access with GIS in Urban Systems (MAGUS) (Matthews, 2003). This tool allows wheelchair users to select which type of wheelchair they are operating (manual or powered) and which barriers they want to avoid throughout their route (Matthews, 2003). From those selections, MAGUS calculates the lowest cost route for the user (Matthews, 2003). The impedance values that correlate with sidewalk and ramp barriers were calculated from the methods discussed previously in Matthews' study (Matthews, 2003). The sidewalk data used to calculate the least cost path of travel were collected by wheelchair users based upon their experiences of traversing the network (Matthews, 2003). The sidewalk problems and barriers identified by participants were manually transferred to GIS. However, the data didn't contain specific measurements related to the sidewalk and ramp problems faced in the field (Matthews, 2003).

Another tool, U-Access, was conceived and implemented on the University of Pitssburgh's campus (Karimi, 2016). U-Access is a website software tool that allows disabled persons to navigate around the University of Pittsburgh campus (Karimi, 2016). The U-Access tool uses a system of nodes and links in GIS to determine the location of pedestrian network and building components that could be difficult for wheelchair users to traverse (Karimi, 2016). These sidewalk and building components include aspects like location of sidewalks, handicapped entrances, handicapped parking, curb ramps, and curb cuts. The locations of these problems were compared to ADA standards and travel time impedance values were assigned using a 'fuzzy inference system' (Karimi, 2016).

Both the U-Access and MAGUS tool have their limitations. The MAGUS tool is not easily transferrable, because it is not publicly available. The MAGUS and U-Access tools also only apply an impedance factor to some of the possible compliance issues. While the researchers using these tools managed to collect a wide variety of pedestrian infrastructure data, there are still holes in terms of the detailed data that need to be collected and compared to ADA standards. The data used in both U-Access and MAGUS are not detailed enough yet to be of practical use for city planners and transportation departments in terms of pedestrian infrastructure maintenance. Unlike the MAGUS tool, the U-Access tool does not take into consideration the actual needs and opinions of disabled persons through the use of survey data and implementation of impedance values.

For routing systems like U-Access and MAGUS to be more impactful, the systems should contain a complete database of all sidewalk and pedestrian infrastructure measurements located along the network. Such systems should also be readily available online and accommodate data additions from new areas. Along with a comprehensive database of all sidewalk problems along a network, travel time impedance values would likely need to be specifically tailored to a local region, and assigned based upon the results of a survey administered in the area. Travel times could be joined with problem details along the traversed network to more accurately assign a travel cost, and route disabled individuals through a lowest cost pathway.

CHAPTER 3. BACKGROUND

The following chapter focuses on Sidewalk Sentry, Sidewalk Scout, and the Midtown data collection process.

3.1 Sidewalk Sentry and Sidewalk Scout

Two publicly available Android applications have been developed by Georgia Tech researchers to aid in the collection of sidewalk data and the assessment of pedestrian infrastructure condition (Frackelton, et al., 2013; Guensler, et al., 2015). The two applications, Sidewalk Sentry and Sidewalk Scout are both semi-automated systems that aid in the collection of sidewalk data in a way that is faster and less expensive than traditional manual methods.

To collect rolling sidewalk video and roughness data, Sidewalk Sentry operates on a tablet affixed to a manual wheelchair. The tablet, using Sidewalk Sentry, collects GPS, accelerometer, and gyroscope data. Accelerometer and gyroscope data are collected at 100Hz and aggregated (RMS) to second-by-second roughness values that correspond with the GPS data along the assessed sidewalk network. The second-by-second accelerometer and gyroscope data from the tablet are processed using server scripts created by Georgia Tech, and allocated to 50-foot sidewalk sections.

3.1.1 Sidewalk Sentry Data Collection Video Review

Sidewalk Sentry videos are uploaded onto a publicly available website and organized by neighborhood in which measurements were taken. Data collectors, participating communities, and interested stakeholders are provided unique logins that give them the ability to access the Sidewalk Sentry website and related data. Users can access and watch the videos located in each neighborhood of interest.

While watching the videos, trained operators can mark the locations of any sidewalk infrastructure problem that does not meet ADA standards. These problems include potholes, obstructions, debris, uneven surfaces, sidewalk width, and manhole/utility cover. Users are also able to mark ramp locations, curb cut locations, crosswalk locations, and where a sidewalk begins or ends. The sidewalk problem data, along with curb ramp, curb cut, and crosswalk location data, are then uploaded onto Georgia Tech's server and integrated into GIS using a table of latitudes and longitudes that indicate the location of each point feature.

A physical report is also generated for each compliance issue. This report displays a picture of the sidewalk issue, the latitude and longitude of the issue, as well as a description of the problem (see Figure 10). These reports, along with point features in GIS, are used by stakeholders to identify, maintain, and prioritize their sidewalk and sidewalk-related assets.

Figure 6 shows the online Sidewalk Sentry system for Midtown. Individual trips can be selected in the map platform or isolated using the scroll bar to the right. From this screen, users can choose trips to review based on their location in Midtown.

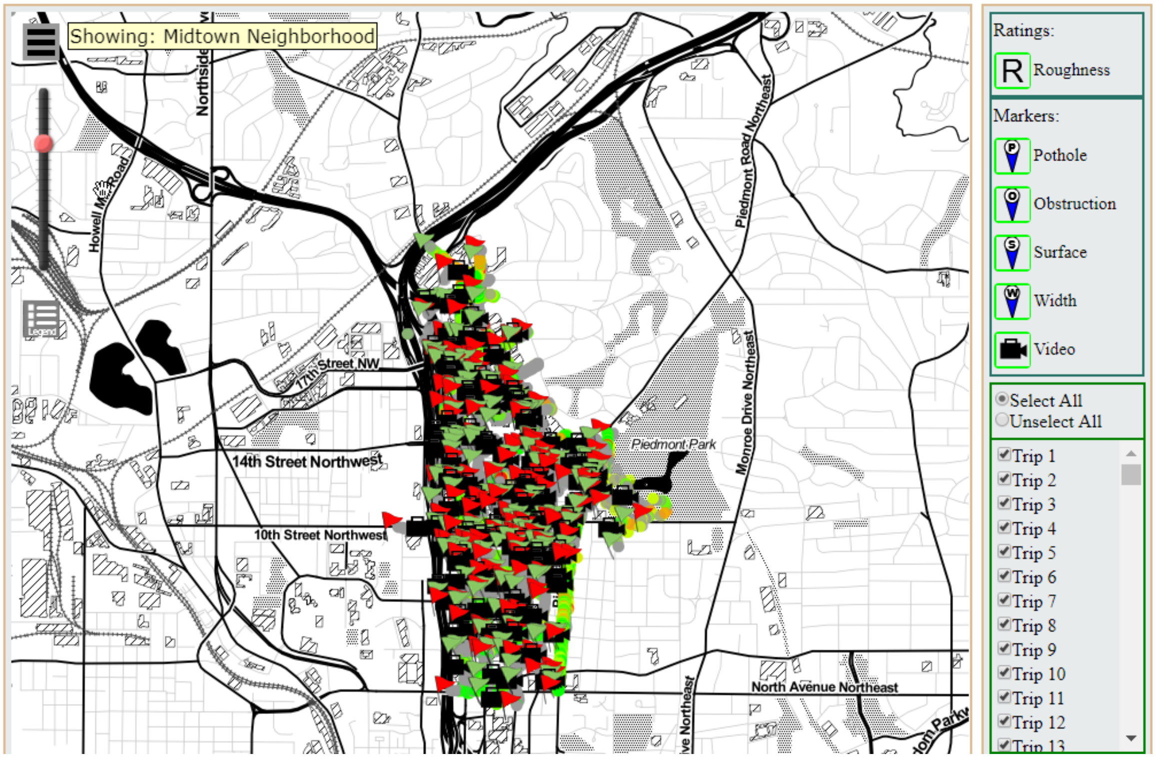

Figure 6. Sidewalk Sentry Online Platform for Midtown

Figure 7 shows the Sidewalk Sentry platform after a trip has been chosen. The rolling video can be viewed on the left-hand side of the screen. The video can be paused, fast-forwarded, or reversed to aid users in the data review process. The entire route, along with second-by-second location is viewed on the right side of the screen. Figure 8 shows what the sidewalk problem display looks like. After a viewer has identified a problem in the rolling sidewalk video, they can choose between the list of displayed sidewalk issues seen in Figure 8.

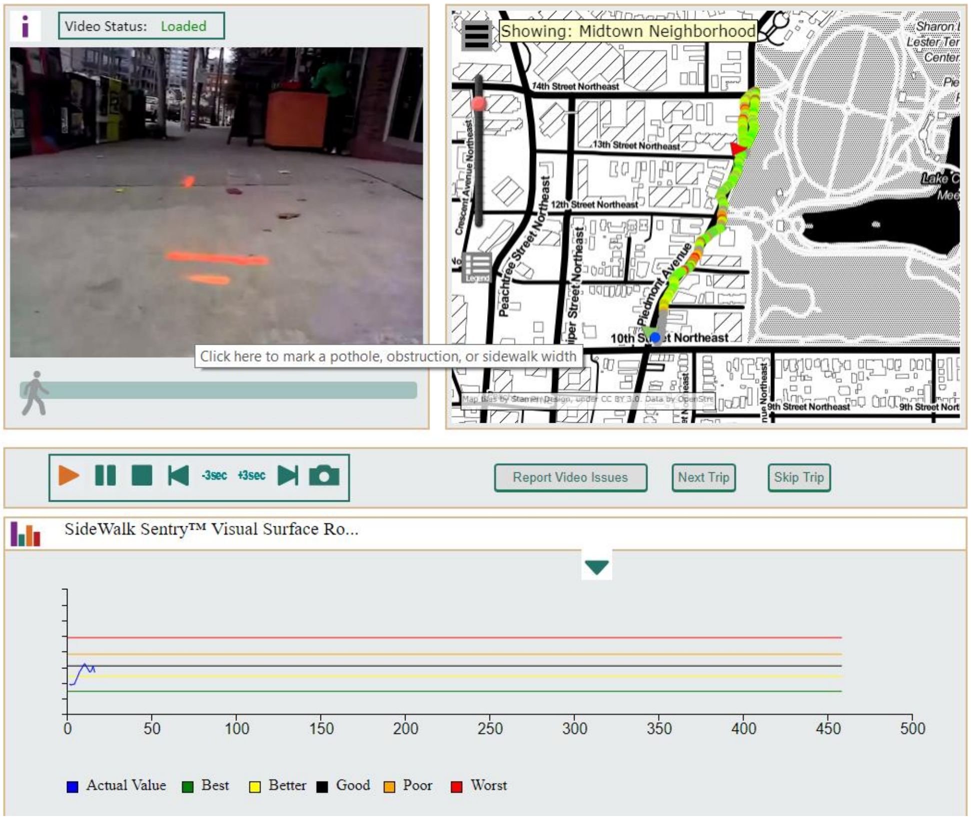

Figure 7. Video Review Interface for Problem Identification

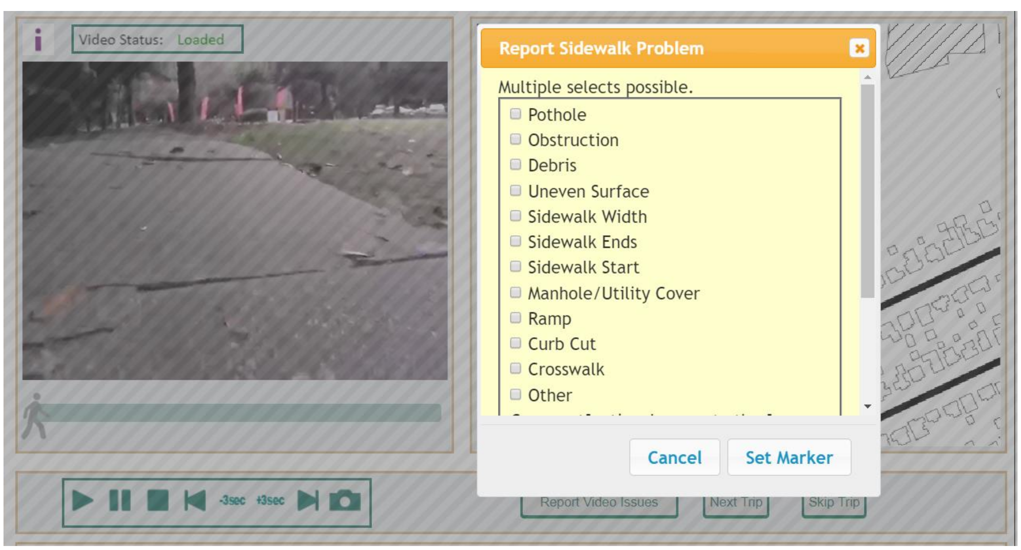

Figure 8. Problem Types used in Video Review

Table 9 details the types of sidewalk problems that are marked using the Sidewalk Sentry system. The types of sidewalk problems that are identified include obstructions, potholes, debris, uneven surfaces, and width issues. The sidewalk problems are derived from design standards set forth by the ADAAG.

Table 9. Descriptions of Sidewalk Problems

Problem	Explanation
Obstruction	A fixed object that cannot be passed by a wheelchair user without exiting the sidewalk path of travel or reducing the functional sidewalk width to less than 3 feet
Pothole	A hole or gap in the sidewalk
Debris	A temporary obstruction (often vegetation or trash) that cannot be passed by a wheelchair user without exiting the sidewalk path of travel or reducing the functional sidewalk width to less than 3 feet
Uneven Surfaces	Disjointed pavement with a vertical displacement greater than ¼ inch
Sidewalk Width	Locations where the width of the sidewalk is less than 3ft

Figure 9 is an example of a generated sidewalk problem report for Midtown. Problem reports are generated for each sidewalk compliance issue in Midtown. Each report identifies the type of problem, its location, and a picture of the issue.

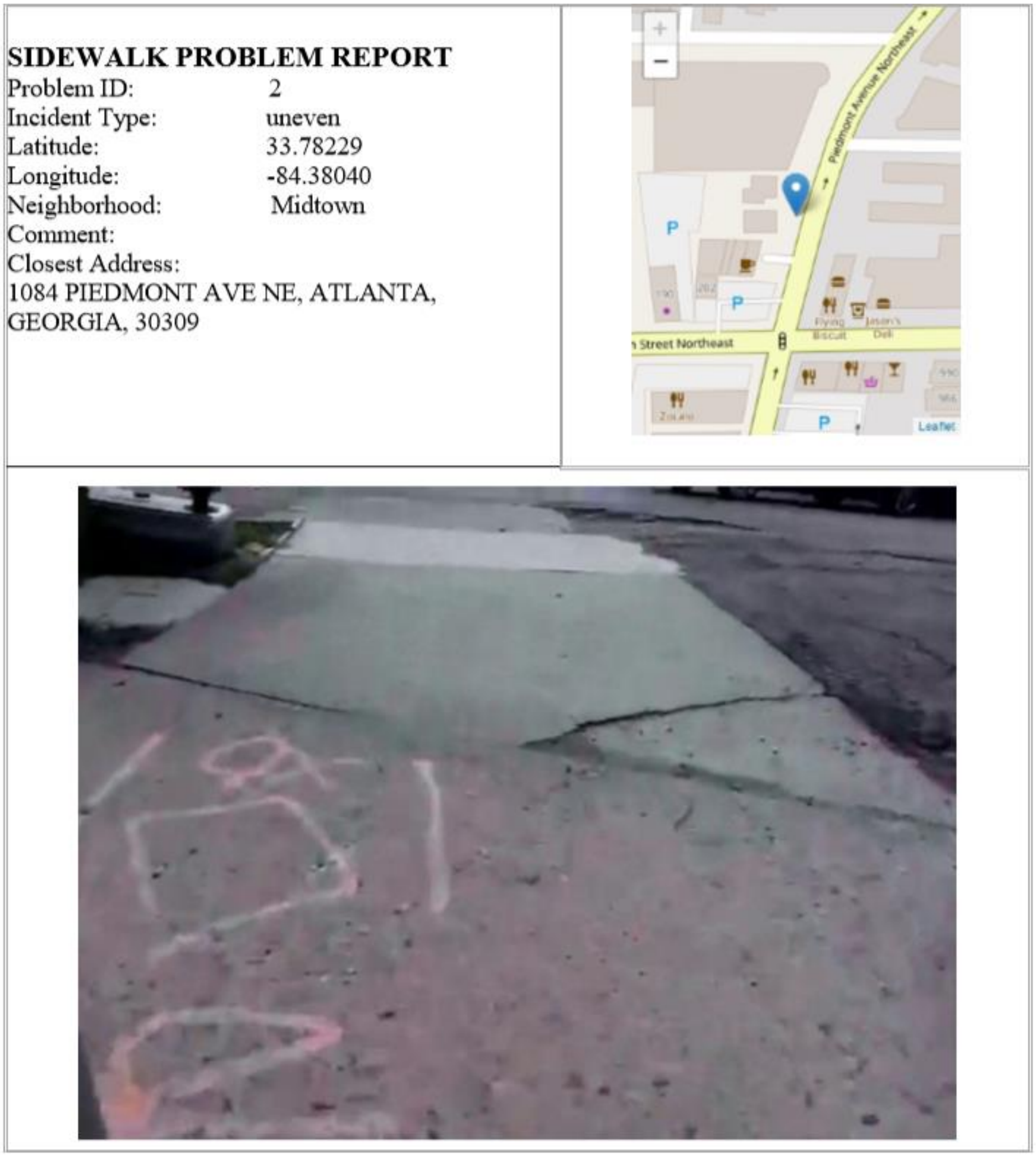

Figure 9. Example of a Server-Generated Sidewalk Problem Report for Midtown

3.1.2 *Sidewalk Scout Data Collection*

Sidewalk Scout is an Android application, primarily downloaded on smartphones, used to collect specific ramp, curb cut, curb, and sidewalk width data. Basic Sidewalk Scout problem reports can be crowdsourced. Any individual can download the basic application and report sidewalk problems. Sidewalk, ramp, and curb cut data can be collected and entered only by individuals that have been assigned an advanced user identification (login) by the Georgia Tech research team (i.e., individuals who have gone through data collection training).

Crowdsourced submissions include a description of the pedestrian infrastructure compliance issue, a picture of the issue, and the location of the issue. Crowd sourced issues are then uploaded to a publicly available map that can be accessed online by anyone. Users with advanced user logins, on the other hand, have the ability to collect detailed curb ramp, curb cut, curb, and sidewalk width data. Initially, the advanced user is prompted to choose which type of sidewalk infrastructure they will measure (a sidewalk location, a curb ramp, or a curb cut).

If a user is taking curb ramp or curb cut measurement, the app opens a new screen that displays images of different types of curb ramps and curb cuts. After selecting the ramp type, the app takes the advanced user to a screen where they are prompted to take a picture of the ramp or curb cut compliance issue. Following the photograph, the user is asked to enter specific ramp or curb cut feature measurements (e.g., ramp width, ramp slope, cross slope, flare slopes, passing width, etc.). These measurements all correspond with ADAAG design requirements (USAB, 2002). Sidewalk measurements are taken in the same manner, the only difference being that there is no initial screen to choose which type of sidewalk is being assessed. All curb ramp, curb cut, and sidewalk width measurements are taken using a standard measuring tape, a Smart Level, a compass, and a smartphone. Figures 10 and 11 show the Sidewalk Scout interface. Figure 12 shows an example of the Sidewalk Scout data entry screen.

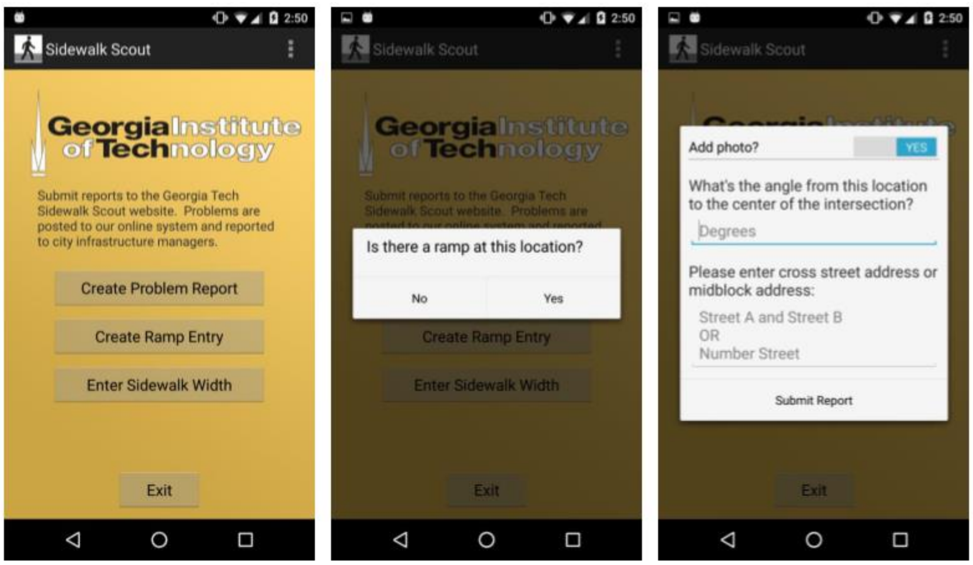

Figure 10. Sidewalk Scout Screen Set-Up for Crowdsourced Problems

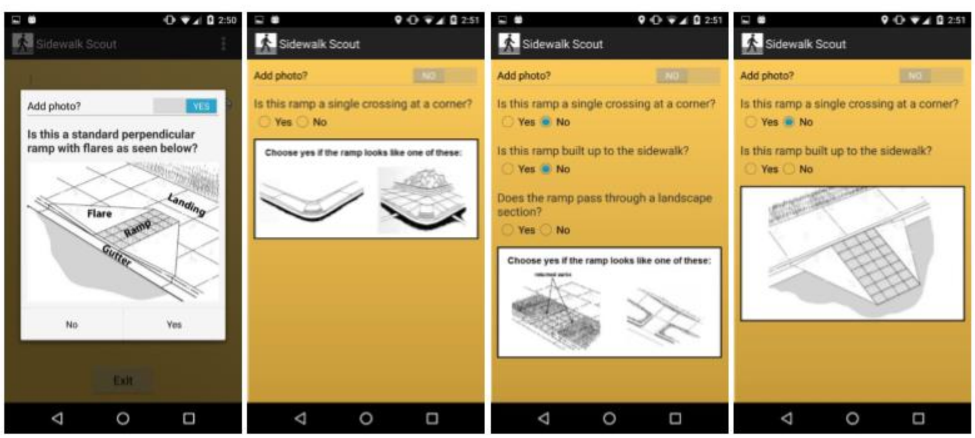

Figure 11. Sidewalk Scout Ramp Type Selection Screens

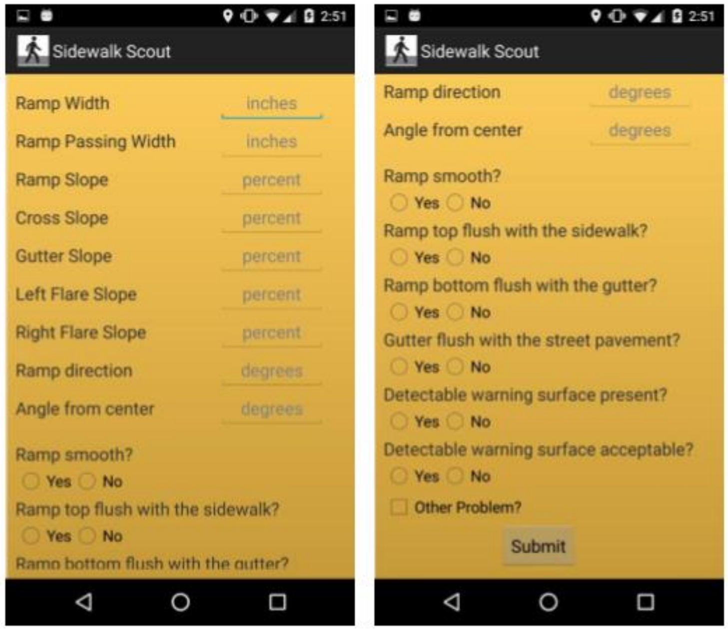

Figure 12. Example of Sidewalk Scout Ramp Data Entry Screens

3.2 Midtown Pedestrian Infrastructure Data

The following section provides background on the neighbourhood of Midtown, Atlanta. The section details the demographics of Midtown as well as the sidewalk data collection process.

3.2.1 Background on Midtown, Atlanta and Purpose of Project

Midtown Atlanta is a mixed-use neighborhood situated between Buckhead and Downtown Atlanta. As of 2014, there were 14,180 residents in Midtown, Atlanta with 49% of them being age 20-24 (Midtown Alliance, 2014). Many new residents are moving into Midtown, which has a population that is growing 5.4 times (3% growth per year) faster than the City of Atlanta itself (Midtown Alliance, 2014). There were 65,000 daytime workers in Midtown in 2014, with one fourth of Atlanta's professional service jobs being located in the 0.9 mi^2 area (Midtown Alliance, 2014). Midtown is one of the most accessible neighborhoods in Atlanta due to its dense development and proximity to MARTA rail and bus lines. Due to the fact that Midtown is one of the densest areas in the city, the neighborhood is one of the most walkable in the city as well. Many of the residents of Midtown claim that they are happy to live in a neighborhood that allows them to live a ‘car-lite’ lifestyle and that the presence of MARTA rail and walkable streets has changed their habits and quality of life (Midtown Alliance, 2018).

While Midtown is one of the most walkable neighborhoods in the city, the neighborhood is still concerned about the state of their pedestrian infrastructure. In 2017, Midtown Alliance, a ‘non-profit membership organization and coalition of leading business and community leaders,’ reached out to Georgia Tech to assess the condition of their sidewalks, curb ramps, and curb cuts (Midtown Alliance, 2018). Midtown Alliance’s goal is to improve infrastructure in the Midtown Core (Midtown Alliance, 2018). Through a partnership with Georgia Tech, Midtown Alliance was provided with a complete database of sidewalk, curb ramp, and curb cut locations and ADA compliance status. The neighborhood is currently using this database for pedestrian infrastructure maintenance and project funding prioritization purposes (Boyer, et al., 2017). The database can aid in maintenance efforts by notifying stakeholders in Midtown of noncompliance issues and problem locations. By analyzing which sidewalk segments, curb ramps, and which curb cuts have the most severe problems, stakeholders can prioritize which pedestrian infrastructure projects to fund first.

3.2.2 Sidewalk Data Collected in Midtown, Atlanta

Sidewalk, curb ramp, and curb cut data were collected in Midtown, Atlanta from January 2017 to November 2017 (Boyer, et al., 2017). Data were collected by trained undergraduate researchers from Georgia Tech using the Sidewalk Sentry and Sidewalk Scout apps. The Midtown network consisted of 40 miles of potential sidewalk locations, assuming that a sidewalk would normally be located on each side of the roadway throughout the area. Approximately 30 miles of sidewalks were present, with the other 10 miles either missing or under construction. Out of the 30 miles of sidewalk in Midtown, 5.3 miles (17.6%) had severe roughness issues. A map of the Midtown sidewalk network with associated roughness values can be seen in Figure 13 below.

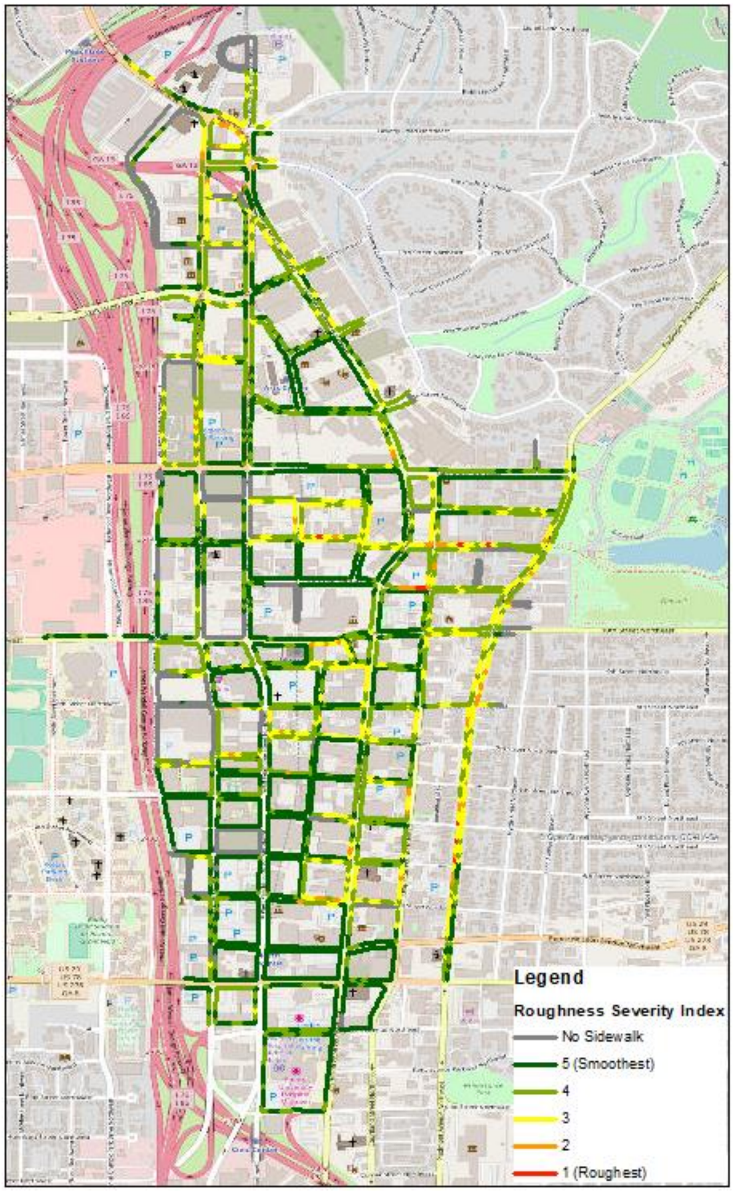

Figure 13. Midtown Sidewalk Network with Associated Roughness Values

Curb ramp data were also collected in Midtown over the ten-month period. The data collectors identified 589 curb ramp locations in Midtown. Of the 589 curb ramps inventoried, 68 (11%) were in compliance with ADA standards, 493 (84%) were not in compliance with ADA standards, and 28 (5%) locations had no curb ramp present. The most common identified ADA compliance issue was ramp cross slopes that exceeded two percent, flare slopes that exceeded ten percent, and running slopes over 8.33% (Boyer, et al., 2017). The complete ramp results and map of locations and ADA compliance can be seen in Figure 14, Figure 15, and Table 10.

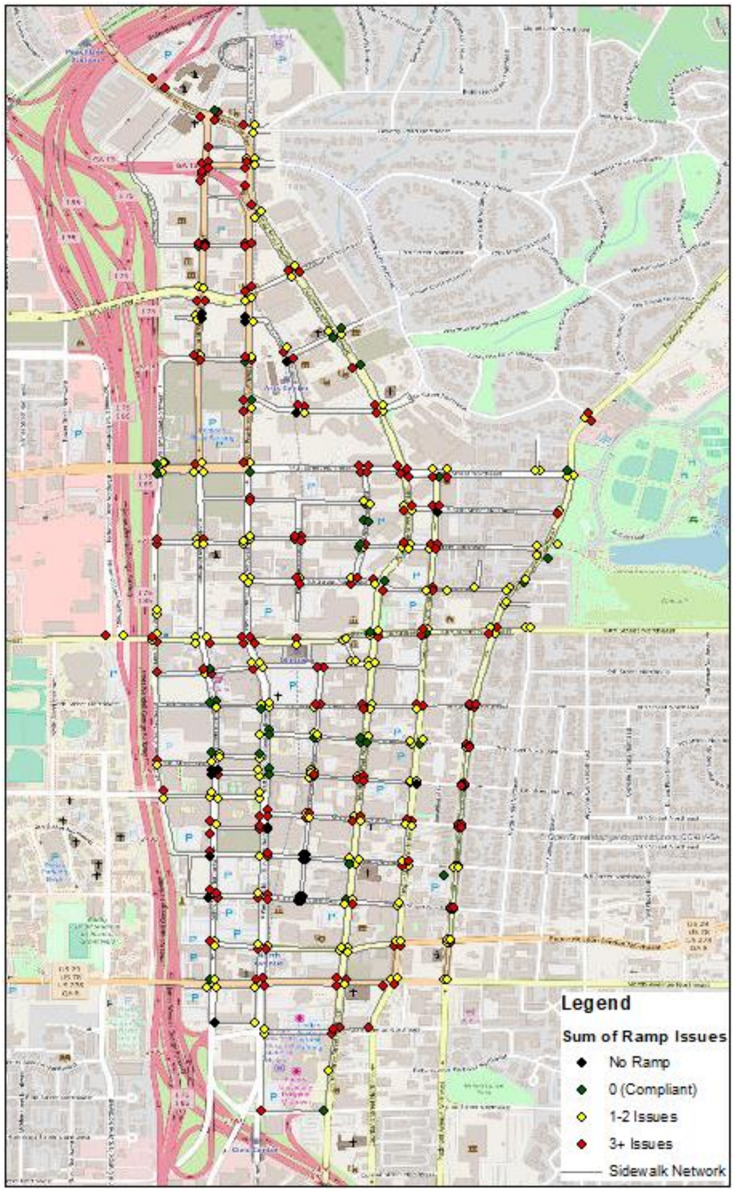

Figure 14. Midtown Curb Ramp Locations and Compliance Status

Table 10. Midtown Curb Ramp Compliance Issues in Midtown, Atlanta

ADAAG Requirement	Num. of Issues	ADAAG Requirement	Num. of Issues
Width (<36”)	**6**	Ramp Flush at Bottom (No)	**45**
Running Slope (>8.33%)	**196**	Ramp Flush at Gutter (No)	**53**
Cross Slope (>2%)	**274**	Detectable Warning Surface Present (No)	**87**
Gutter Slope (>5%)	**110**	Detectable Warning Surface Condition (Not Compliant)	**11**
Left Flare Slope (>10%)	**216**	Left Transition Slope (>8.33%)	**5**
Right Flare Slope (>10%)	**201**	Right Transition Slope (>8.33%)	**4**
Passing width (<36”)	**50**	Landing Slope (>2%)	**7**
Ramp Surface Not Smooth	**23**	Landing Width (<60”)	**2**
Ramp Flush at Top (No)	**9**	Ramp Missing	**28**

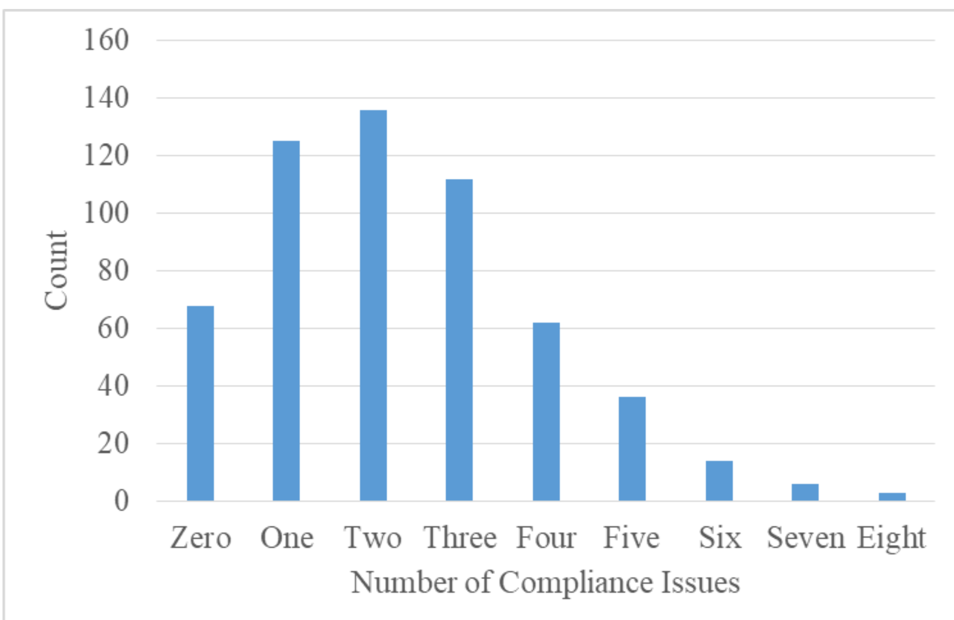

Figure 15. Number of ADA Compliance Issues per Curb Ramp in Midtown, Atlanta

Curb cut data was also collected in Midtown over the ten-month period. The data collectors identified 764 curb cut locations in Midtown. Of the 764 inventoried curb cuts, 168 (22%) were in compliance with ADA standards and 596 (78%) were not in compliance with ADA standards. The most common compliance issues were uneven curb cut surfaces and cross slopes exceeding 2%. The complete curb cut compliance issues and curb cut locations can be seen in Figure 16, Figure 17, and Table 11.

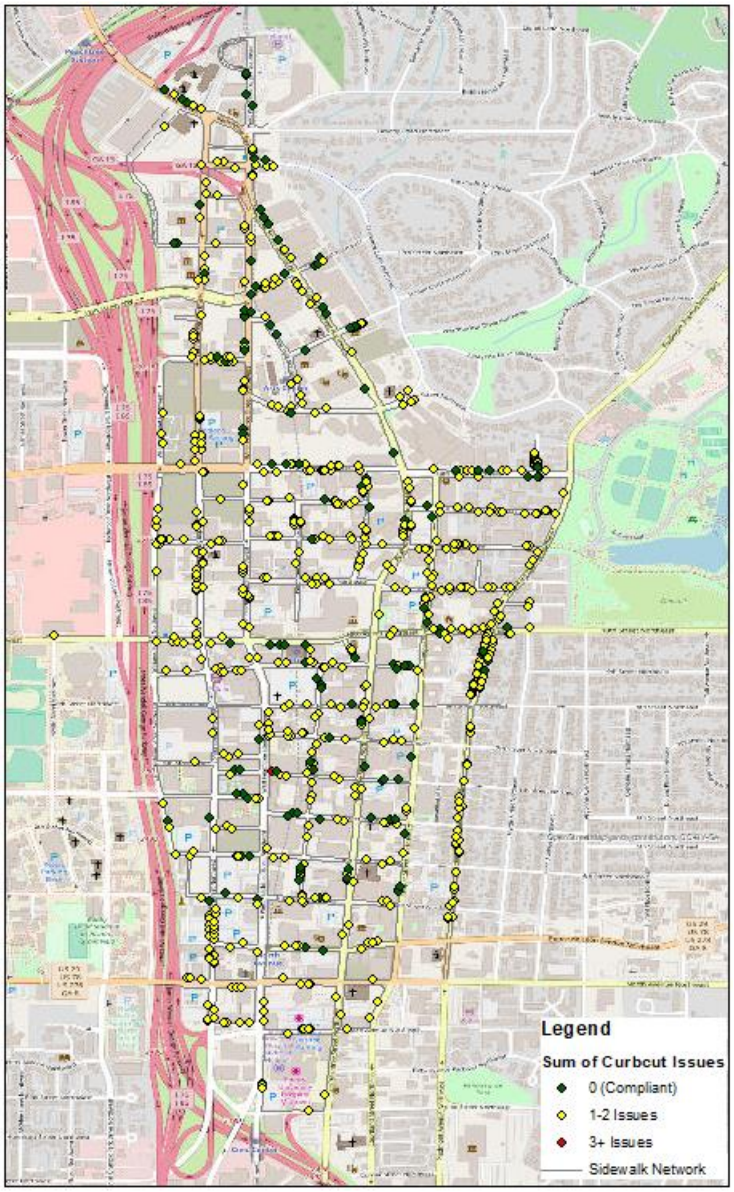

Figure 16. Midtown Curb Cut Locations and Compliance Status

Table 11. Identified Curb Cut Compliance Issues in Midtown

ADAAG Requirement	Num. of Issues
Cross Slope (>2%)	278
Curb cut Surface Not Smooth	363
Passing Width (<36")	4
Left Sidewalk Ramp Slope (>8.33%)	1
Right Sidewalk Ramp Slope (>8.33%)	2
Left Sidewalk Ramp Cross Slope (>8.33%)	2

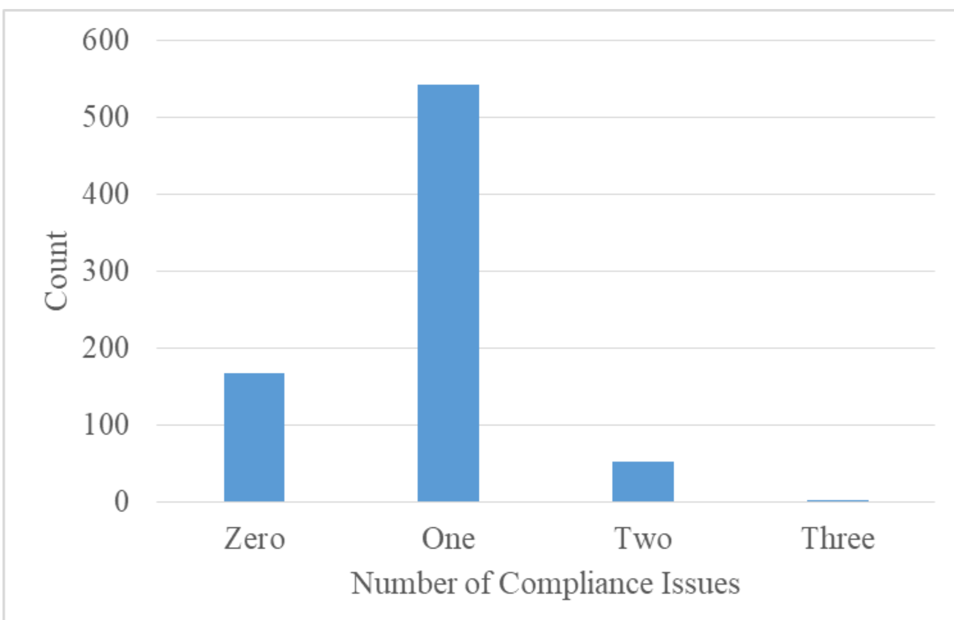

Figure 17. Number of ADA Compliance Issues per Curb Cut

After processing the Sidewalk Sentry rolling video for Midtown, the research team identified 538 sidewalk defects. The most common ADA compliance issues were uneven surfaces and debris along the sidewalk network. A map of sidewalk problem locations and the number of each sidewalk issue can be seen in Figure 18 and Table 12.

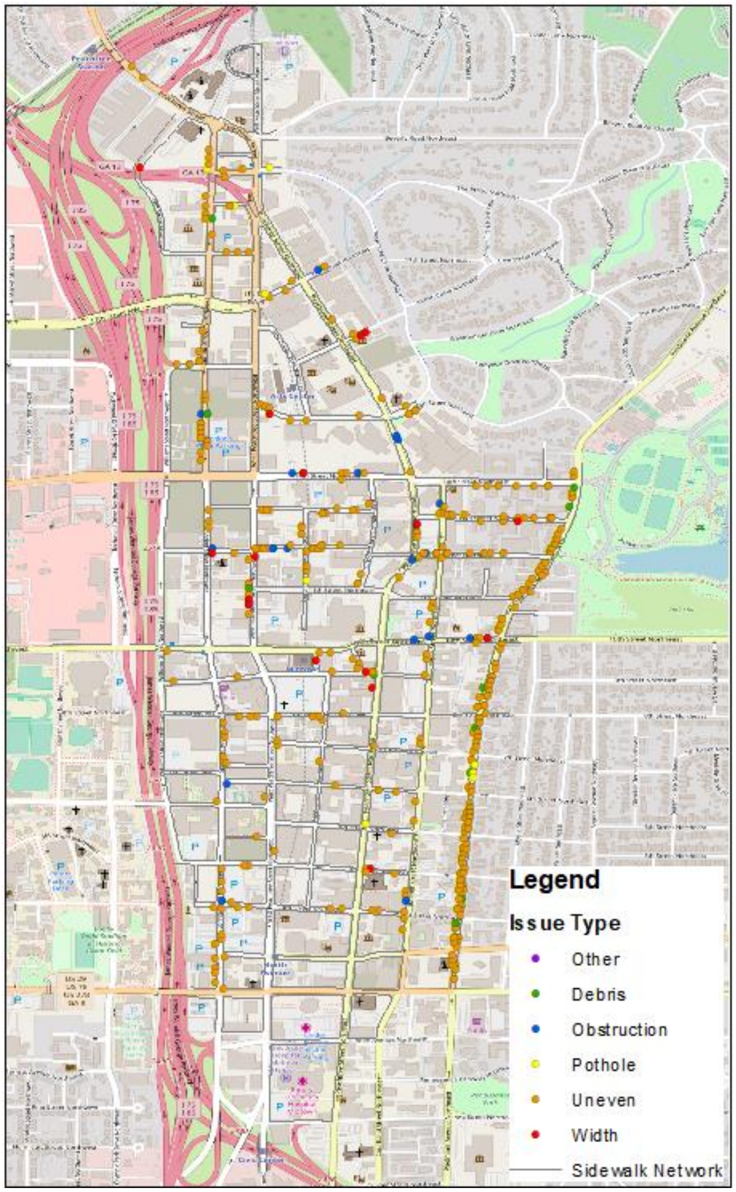

Figure 18. Midtown Sidewalk Problem Locations

Table 12. Identified Sidewalk Compliance Issues in Midtown, Atlanta

Sidewalk Problem	Number of Issues
Pothole	17
Uneven Surface	436
Obstruction	29
Debris	33
Width Issue	18

CHAPTER 4. METHODOLOGY

4.1.1 Methodology Overview

Network Analyst in ArcGIS is used to assess the travel time along the Midtown sidewalk network before and after the addition of travel time impedances attributed to sidewalk problems. Because a survey of wheelchair users is not currently available for the Midtown area, the findings from the literature review of previous studies will be used to assign impedance values to compliance issues along the Midtown network. There were four main takeaways from previous studies on the effects of sidewalk problems on wheelchair users. The key takeaways from the literature review of sidewalk problems include:

- The presence of steps is the largest barrier for wheelchair users traversing a network (steps are extremely difficult or impossible to overcome)
- A lack of curb ramps or inadequate curb ramps was the second largest barrier for wheelchair users to overcome
- Steep slopes along the network were a major problem identified in all of the studies
- Uneven surfaces along the network proved difficult for wheelchair users to navigate
- The physical ability of wheelchair users plays a large role in how hard it is to overcome uneven surfaces

Using these four takeaways, a set of five different impedance values were assigned to the sidewalk problems to assess travel time. Analyzing travel time over a range of impedance values is undertaken because no definitive set of values can be assigned until survey data are collected from wheelchair users in Midtown. Analyzing travel time results over a range of values will also shed more insight on how different types of pedestrian infrastructure compliance issues, and their frequency, effect wheelchair users' pathways.

'Steps' were the most problematic sidewalk barrier according to the literature review, however there were no instances of steps along the Midtown sidewalk network. Steps serve as an obstruction for wheelchair users and impede the sidewalk path. An extreme amount of effort may be required for a wheelchair to overcome an obstruction that is present in their travel path. Obstructions can cause wheelchair users to move off of a sidewalk and into the road or buffer area. Obstructions can even require a wheelchair user to turn around. For continuity, the obstructions identified in Midtown will be treated in the same manner as they were in the previous studies.

Five sets of impedance values will be explored. The first set of impedance values will add an equal amount of travel time impedance for each type of sidewalk, ramp, and curb cut problem in Midtown. The other four sets of impedance values will each put a higher emphasis on one of the more critical sidewalk problems identified in the literature review of previous studies. These impedance values will range from a minimum added travel time of three seconds, for minor defects, to a maximum added travel time of ten seconds, for moderate defects. Missing sidewalks, gaps in the sidewalk network, as well as corners with two missing ramps will be treated as pathway barriers in this analysis. Sidewalk sections in the network that incorporate barriers in the network analysis will be assumed to be impassible. Hence, barrier sections add the most travel time to the shortest path calculation because a longer path is required. The second set of impedance values will place the highest impedance value on non-compliant slopes in the sidewalk network. The third set of impedance values will place the highest impedance value on uneven surfaces, potholes, and roughness throughout the sidewalk network. The fourth set of impedance values will place the highest impedance value on obstructions throughout the sidewalk network. The fifth and final set of impedance values will mark obstructions and sidewalk and ramp width problems throughout the network as barriers that cannot be overcome.

All five travel time analyses will be compared to a base analysis that applies no travel time impedance values to barriers along the network. The base analysis is considered an able-bodied travel time estimation, because none of the sidewalk quality issues being assessed in this analysis will significantly affect the travel time or ability of an able-bodied person to move from origin to destination. This is similar to real-word scenarios where able-bodied individuals can either step over sidewalk compliance issues, cross streets with no curb ramps, or traverse along paths with no sidewalk or slope problems.

4.1.2 Network Analyst and Dijkstra's Algorithm

The OD-Cost Matrix function of the Network Analyst extension in GIS is used in this travel time analysis. The OD-Cost matrix function uses multiple origins and destinations to calculate the shortest path between points (ESRI, 2017). The routing methodology used in the Network Analyst function is based on Dijkstra's shortest path algorithm (ESRI, 2017). Dijkstra's algorithm was created by Edsger Dijkstra in 1956 and is one of the most common ways to calculate the shortest path between a node *s* and all other nodes (Richards, 2012). Dijkstra's algorithm begins by assigning 'an initial value for the distances from node *s* and to all other nodes' (Wolfram, 2017). Dijkstra's algorithm operates in steps and at each step, the algorithm reevaluates and improves the shortest path between each node and all other nodes (Brandes, 2000). Dijkstra's algorithm is based on the principle that the minimum cost from the origin and destination will eventually be found while also calculating the minimum cost between the origin and all other nodes in the network. While Dijkstra's algorithm can be calculated manually, the presence of present-day technology and computer power allow for this algorithm to be easily used to calculate the shortest distance and minimum cost between points. Dijkstra's algorithm is commonly used in computer science, warehouse optimization, as well as transportation applications (Perenic, 2011). Dijkstra's algorithm is modified in the Network Analyst extension to better represent real-word transportation problems (ESRI, 2017). Settings such as 'one way restrictions, turn restrictions, junction impedance, barriers, and side-of street constraints' can be modified in GIS to more accurately represent the transportation network at hand (ESRI, 2017). Costs can also be added to features along the network. These costs are taken into consideration when calculating the shortest path. Examples of costs that can be set by users can be time, distance, or a variety of other parameters (ESRI, 2017). Commonly used navigation applications like Google Maps and Waze also use Dijkstra's algorithm to calculate the most efficient network pathways from origin to destination.

4.1.3 Midtown Sidewalk Network Generation

A sidewalk network composed of links and nodes must first be generated before shortest path algorithms can be applied to travel. For an urban setting, the first modeling assumption is that sidewalks have at some time in the past been constructed alongside of all roadways. The number of miles of sidewalks in an urban area should be approximately twice that of roadway networks. Roadway network shapefiles for use in GIS are usually readily available, either directly from the applicable cities and municipalities, by downloading federal Tiger networks, or by visiting publicly available GIS portals. GIS shapefiles for sidewalk networks, on the other hand, are not readily available. Most cities and municipalities do not have a GIS shape file for their sidewalk network, and in many instances cities have no inventory of sidewalks locations (whether the sidewalks exist or don’t exist in their area).

In the Midtown sidewalk data collection effort, the Georgia Tech team first developed a sidewalk network using a variety of GIS tools. The sidewalk network was generated using roadway centerline files and parcel data for the Midtown area (Li, 2017). Sidewalk links are generated in locations were sidewalks should be using the edges of the Midtown parcel polygons in GIS and the adjacent roadway (Li, 2017). For the Midtown case study, sidewalks were expected to be present in front of every land use parcel on each side of the adjacent roadway. The sidewalk network is then broken into 50-foot segments, to make summarizing sidewalk data that is joined to the network easier (Li, 2017). Dividing the sidewalk into 50-foot segments aids in the planning process by giving planners and engineers the ability to assess the condition of sidewalks on an individual basis, instead of the network as a whole.

To generate ramp nodes in an automated fashion, roadway intersections are identified and a buffer is created around the nearby sidewalk network (Li, 2017). Any nodes within this buffer are designated ramp nodes, because they are present at an intersection of two roadways (Li, 2017). Crosswalk links are then generated between each ramp node in the system (Li, 2017). Hence, for a four-legged intersection, four sidewalk nodes appear at each intersection and ramps should be associated with each node based upon ADA design standards. At each corner node, up to two ramps could actually be present on site depending on the type and orientation of the ramp.

4.1.4 Roughness Data

The tablet used to collect data with the Sidewalk Sentry application collects accelerometer data in the x, y and z directions and gyroscope rotation data around each axis. Both the gyroscope data and accelerometer data are automatically linked to GPS points collected concurrently along the sidewalk network using the common satellite time stamp. The raw second by second GPS, accelerometer, and gyroscope data are uploaded from the tablet and processed using a script that categorizes the sidewalk vibration values on a scale from 1 (Most Rough) to 5 (Smooth). The 1-5 ranking system was calculated using k-means cluster analysis in R. K-means cluster analysis was used to find natural breaks in the raw vibration data extracted from the tablet. The purpose of K-means clustering analysis is to classify data into k number of clusters, while also minimizing the variation within each cluster (University of Cincinnati, 2016). The variation within each cluster is classified by calculating the variation as the sum of squared distances between points (University of Cincinnati, 2016). By minimizing the total summed squared distances between all points through multiple iteration processes in R, dissimilar clusters can be identified (University of Cincinnati, 2016). Using this methodology, and assigning a value of 5 to k, unique roughness groupings were produced and used to rate the roughness of sidewalk links in Midtown. Roughness points along each 50-foot sidewalk link are averaged, resulting in a final roughness value (from one to five) for each link.

4.1.5 Data Aggregation and Network Building Methodology

The collected Midtown sidewalk data were converted from latitude and longitude into point and line features in GIS. Ramps and sidewalk problems (obstructions, potholes, width issues, uneven surfaces, etc.) were converted into point features, while curb cuts were converted into line features. The roughness values were aggregated and averaged over each 50-foot sidewalk segment. Each point and line feature contains an attribute table of all data collected in the field. These data are compared to ADA standards and each measurement is assigned a value of 1 or a 0, based on whether the attribute meets ADA standards. The 1 and 0 values are then summed for each ramp and curb cut to calculate a final compliance value, where 0 means that the ramp or curb cut meets all ADA standards. Each sidewalk problem reported from sidewalk sentry is imported into GIS, with an attribute table that indicates the type of issue and any comments associated with the issue. Each 50-foot sidewalk segment is also assigned the average of the roughness values, which scales from 1 to 5. All of these data are compiled into a single GIS database.

For each of the five sets of impedance values run for the analyses, features were assigned a travel-time impedance according to the type of problem observed. For ramps that had more than one compliance issue, the impedance values for each of the noncompliant aspects were added together to obtain an overall travel time impedance for the ramp. Sidewalk segments that had more than one compliance issue were treated in the same way as ramps, where the impedance values are summed for each 50-foot segment with problems. The travel time impedance value associated with curb cuts was summed for each noncompliant curb cut, as well.

Five hundred random origins and destinations were created on the Midtown network in GIS. A network was built in ArcGIS that included the sidewalk network, crosswalks, and the associated junctions. With no sidewalk problems present, each of the 500 destinations can be reached from the 500 origins by moving along the sidewalk network, resulting in a total of 250,000 possible trips. A walking speed of 2.5 mph was programmed into the network build, indicating the speed at which a wheelchair user is expected to move along the network. Each of the five sets of impedance values were coded along the network and analysis were run for each set independently. Pedestrian infrastructure problems that can be overcome by a wheelchair user were designated as an added cost barrier in GIS. The added cost is based on the time-travel impedance value associated with each ramp, curb cut, sidewalk segment, or sidewalk compliance issue. Instances of missing sidewalks or sidewalk gaps throughout the network were designated as a restriction. Restrictions prohibit travel anywhere on the sidewalk segment upon which the restriction is located. Each of the five sets of impedance values were solved for using the OD Cost Matrix Function. Total travel time, average travel time, maximum travel time, total length travelled, and average trip length are the products of running the OD Cost Matrix.

CHAPTER 5. RESULTS

The following chapter discusses the results of the travel-time impedance analysis using Network Analyst. The results of each set of impedance values are compared to one another to determine which type of compliance issues have the largest burden on wheelchair users.

5.1 Iteration Zero- Baseline Conditions

The purpose of iteration zero is to provide a constant variable condition to which the five iterations can be compared. The baseline condition represents the total and average travel time for the modelled shortest path trips, assuming that there are no sidewalk, ramp, or curb cut deficiencies of significance along the network, and assuming that an able-bodied user would be unaffected by any sidewalk, ramp, or curb cut compliance issues. Iteration zero is the only iteration in which all 250,000 trips from origin to destination can be successfully completed, because there are no barrier restrictions or travel time impedance values associated with the network. Results for iteration zero are presented below in Figure 19 and trip statistics are summarized in Table 13. The random nature of the trips makes the average trip very long (unreasonably so). The following analysis is a large-scale assessment that includes a large variety of trip lengths to examine the effect compliance issues have on travel time. In a real-world scenario, a maximum analysis of 0.25 to 0.5 miles would be made in order to model logical walking mode choice decisions.

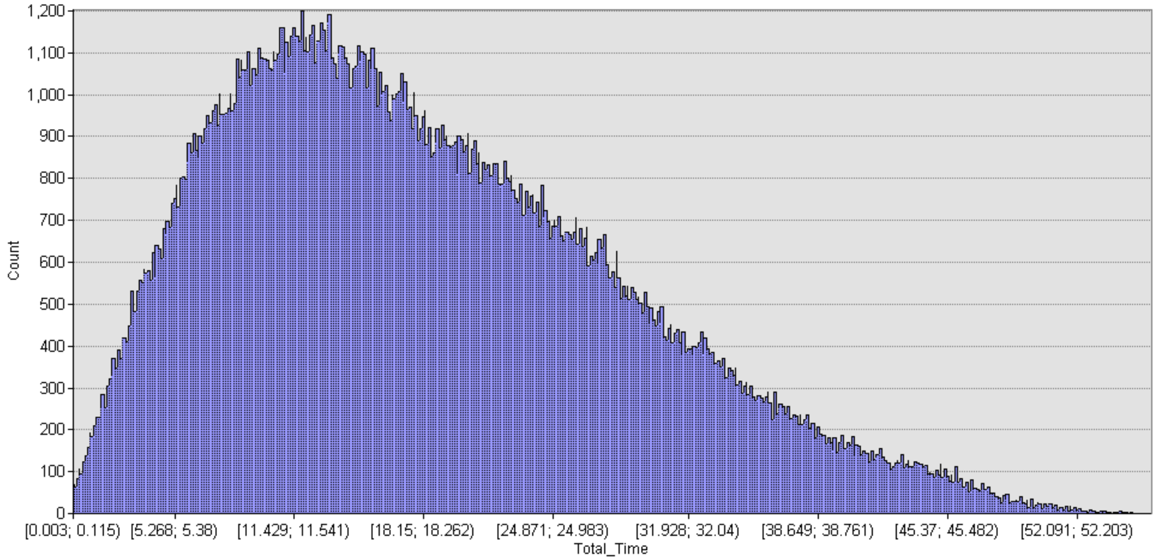

Figure 19. Frequency Distribution of Travel Time for Base Condition

Table 13. Iteration Zero Trip Statistics

Trip Attribute	Value
Number of Trips Completed	250,000 trips
Total Travel Time	4,593,616 minutes
Average Trip Travel Time	18.37 minutes
Maximum Travel Time	56.01 minutes
Total Distance Traveled	1010691592 feet
Average Trip Length	4042.8 feet
Trips Unable to be Made	0 trips

5.2 Iteration One

The first set of impedance values assigned the same added travel time to each sidewalk, curb ramp, and curb cut problem. Areas where no sidewalk exist acted as a barrier restriction along the network. The tables and figures below show the added cost associated with each problem as well as the results from the network analysis. For this iteration, sidewalk problems include width, obstruction, and debris. Slope problems include sidewalk cross slopes, sidewalk running slopes, ramp running slopes, ramp cross slopes, ramp gutter slopes, ramp flare slopes, and all related curb cut slope issues. Surface problems include uneven sidewalk surfaces, potholes, non-compliant ramp surfaces, non-compliant curb cut surfaces, and sidewalk roughness. The assigned travel time impedance values and can be seen in Table 14. Results for Iteration One can be seen in Figure 20 and trip statistics are summarized in Table 15.

Table 14. Travel Time Impedance Values for Iteration One (Equal focus)

Each Sidewalk Problem	5 seconds
Each Slope Problem	5 seconds
Each Surface Issue	5 seconds

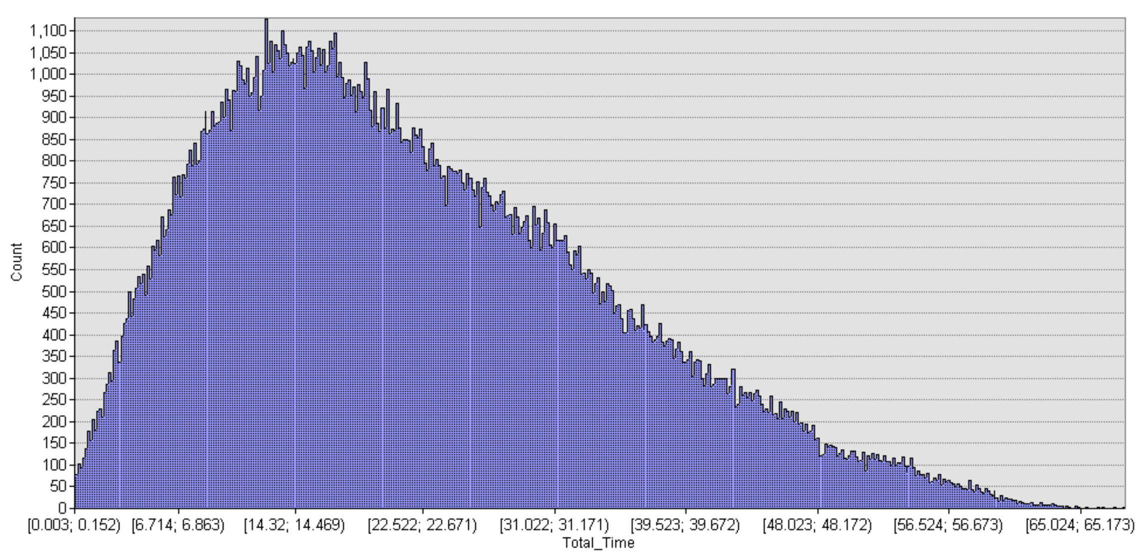

Figure 20. Frequency Distribution of Travel Time for Iteration One

Table 15. Network Analyst Results for Iteration One (Equal Focus)

Trip Attribute	Value
Number of Trips Completed	208,779 trips
Total Travel Time	4,615,560 minutes
Average Trip Travel Time	22.11 minutes
Maximum Travel Time	68.00 minutes
Total Length Traveled	901,838,766 feet
Average Trip Length	4319.6 feet
Trips Unable to be Made	41,221 trips

For iteration one, 41,221 trips could not be completed. These trips had either origins or destinations on parts of the network that did not have sidewalks or that had sidewalks under construction. The origins and destinations in these locations were isolated by construction or lack of sidewalks in either both or one of the locations.

5.3 Iteration Two

The second set of impedance values assigned a higher impedance value to slope compliance issues along the network. Sidewalk width problems were assigned the second highest impedance value, and surface problems were assigned the lowest impedance value.

Areas where no sidewalk exist acted as a barrier restriction along the network. For this iteration, slope problems include sidewalk cross slopes, sidewalk running slopes, ramp running slopes, ramp cross slopes, ramp gutter slopes, ramp flare slopes, and all related curb cut slope issues. Width issues are considered to be any point where there is an obstruction or where the sidewalk width, ramp width, or ramp passing width does not meet ADA standards. Surface problems include uneven sidewalk surfaces, potholes, non-compliant ramp surfaces, non-compliant curb cut surfaces, and sidewalk roughness. The assigned travel time impedance values and results for iteration two can be seen in Table 16, Table 17, and Figure 21.

Table 16. Travel Time Impedance Values for Iteration Two (Focus on Slopes)

Each Slope Issue	10 seconds
Each Width Issue	5 seconds
Each Surface Issue	3 seconds

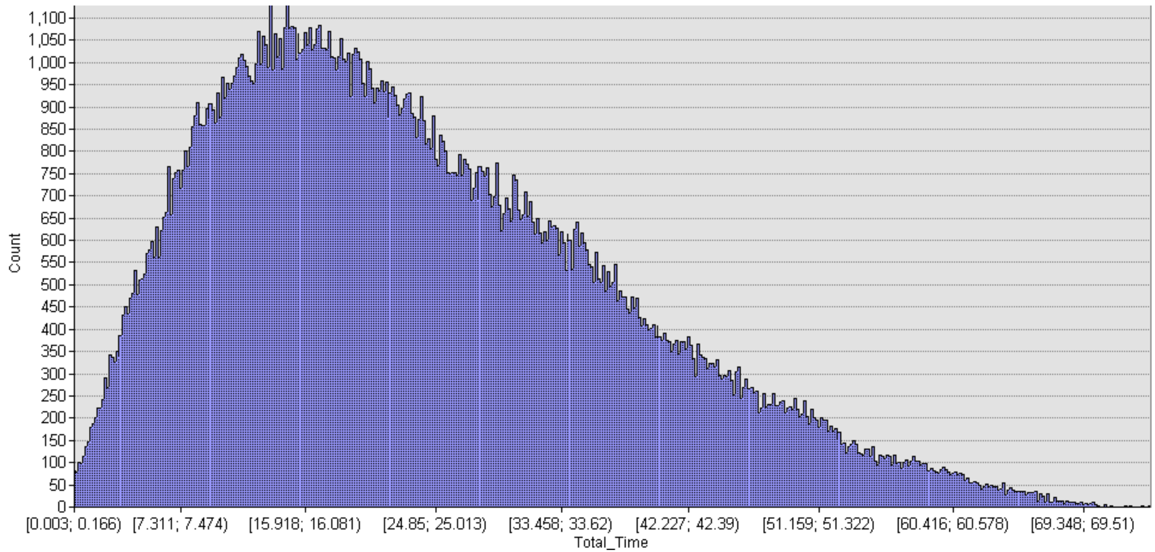

Figure 21. Frequency Distribution of Travel Time for Iteration Two

Table 17. Network Analyst Results for Iteration Two (Focus on Slopes)

Trip Attribute	Value
Number of Trips Completed	208,779 trips
Total Travel Time	4,982,375 minutes
Average Trip Travel Time	23.86 minutes
Maximum Travel Time	74.05 minutes
Total Length Traveled	925,234,205 feet
Average Trip Length	4431.6 feet
Trips Unable to be Made	41,221 trips

For iteration two, 41,221 trips were unable to be made. These trips had either origins or destinations on parts of the network that did not have sidewalks or that had sidewalks under construction.

5.4 Iteration Three

The third set of impedance values assigned a higher impedance value to surface compliance issues along the network. Sidewalk and ramp width problems were assigned the second highest impedance value, and slope problems were assigned the lowest impedance value. Areas where no sidewalk exist acted as a barrier restriction along the network. For this iteration, surface problems included uneven sidewalk surfaces, potholes, non-compliant ramp surfaces, non-compliant curb cut surfaces, and sidewalk roughness. Width issues were considered to be any point where there is an obstruction or where the sidewalk width, ramp width, or ramp passing width does not meet ADA standards. Slope problems include sidewalk cross slopes, sidewalk running slopes, ramp running slopes, ramp cross slopes, ramp gutter slopes, ramp flare slopes, and all related curb cut slope issues. The assigned travel time impedance values and results for iteration three can be seen in Table 18, Table 19, and Figure 22.

Table 18. Travel Time Impedance Values for Iteration Three (Surface Issue Focus)

Surface Issues	10 seconds
Width Issues	5 seconds
Slope Issues	3 seconds

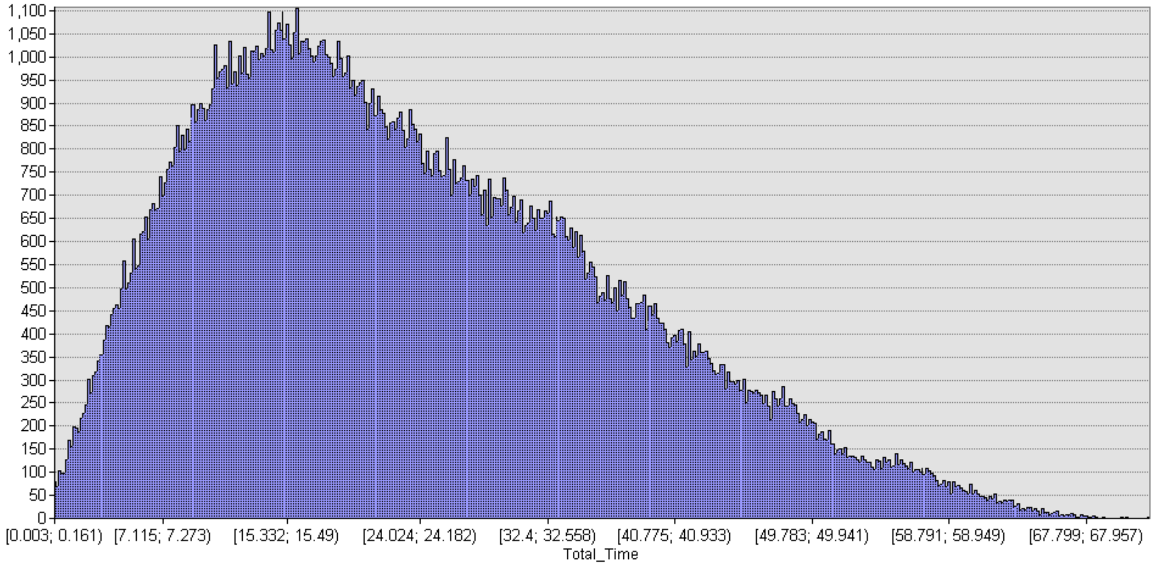

Figure 22. Frequency Distribution of Travel Time for Iteration Three

Table 19. Network Analyst Results for Iteration Three

Trip Attribute	Value
Number of Trips Completed	208,779 trips
Total Travel Time	4,947,363 minutes
Average Trip Travel Time	23.70 minutes
Maximum Travel Time	72.10 minutes
Total Length Traveled	911,340,142 feet
Average Trip Length	4365.0 feet
Trips Unable to be Made	41,221 trips

For iteration three, 41,221 trips could not be completed. These trips had either origins or destinations on parts of the network that did not have sidewalks or that had sidewalks under construction.

5.5 Iteration Four

The fourth set of travel time impedance values assigned a higher travel time impedance value to obstructions along the network. Sidewalk and ramp width problems were assigned the second highest impedance value, and both surface and slope problems were assigned the lowest impedance value. Areas where no sidewalk exist acted as a barrier restriction along the network. For this iteration, obstructions are considered to be any fixed object along the network that reduces the sidewalk width to less than three feet. Width issues are considered to be any point where the sidewalk width, ramp width, or ramp passing width does not meet ADA standards. Surface problems include uneven sidewalk surfaces, potholes, non-compliant ramp surfaces, non-compliant curb cut surfaces, and sidewalk roughness. Slope problems include sidewalk cross slopes, sidewalk running slopes, ramp running slopes, ramp cross slopes, ramp gutter slopes, ramp flare slopes, and all related curb cut slope issues. The assigned travel time impedance values and results for iteration four can be seen in Table 20, Table 21, and Figure 23.

Table 20. Travel Time Impedance Values for Iteration Four (Width Focus)

Obstructions	10 seconds
Width Issues	5 seconds
Slope Issues	3 seconds
Surface Issues	3 seconds

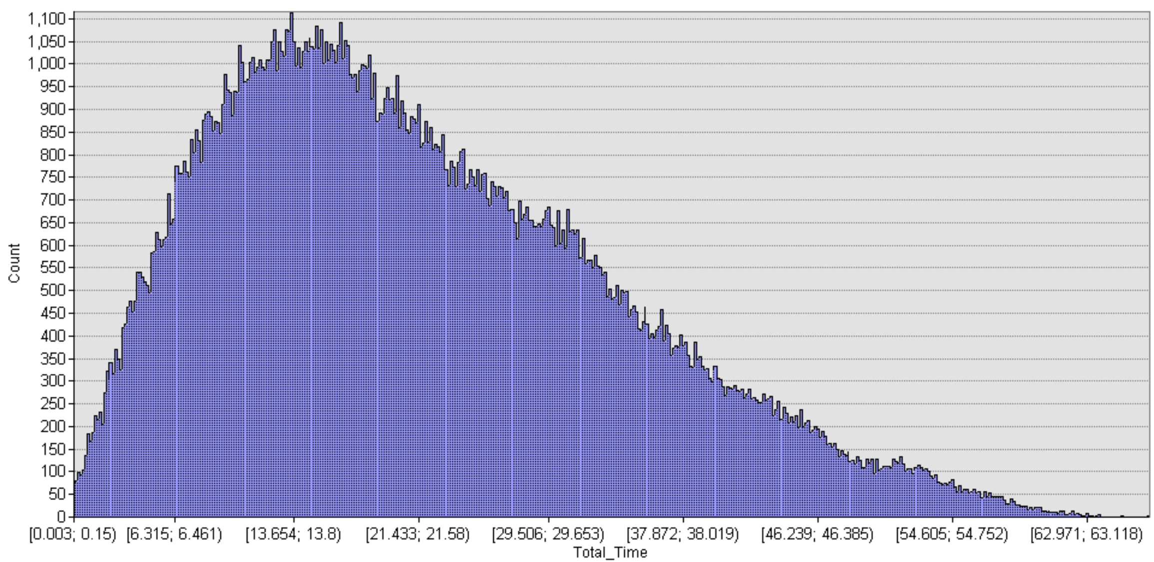

Figure 23. Frequency Distribution of Travel Time for Iteration Four (Width Focus)

Table 21. Network Analyst Results for Iteration Four (Width Focus)

Trip Attribute	Value
Number of Trips Completed	208,779 trips
Total Travel Time	4,527,905 minutes
Average Trip Travel Time	21.70 minutes
Maximum Travel Time	66.90 minutes
Total Length Traveled	897,243,806 feet
Average Trip Length	4297.6 feet
Trips Unable to be Made	41,221 trips

For iteration four, 41,221 trips were unable to be completed. These trips had either origins or destinations on parts of the network that did not have sidewalks or that had sidewalks under construction.

5.6 Iteration Five

The fifth set of travel time impedance values assigned obstructions and width issues as sidewalk network restrictions. These two types of issues, along with areas on the network with no sidewalk or sidewalks that are under construction, are unable to be traversed. For this iteration, obstructions are considered to be any fixed object along the network that reduces the sidewalk width to less than three feet. Width issues, in this case, consist of sidewalk width problems, ramp width problems, and ramp passing width problems. Surface problems include uneven sidewalk surfaces, debris, potholes, non-compliant ramp surfaces, non-compliant curb cut surfaces, and sidewalk roughness. Slope problems include sidewalk cross slopes, sidewalk running slopes, ramp running slopes, ramp cross slopes, ramp gutter slopes, ramp flare slopes, and all related curb cut slope issues. The assigned travel time impedance values and results for iteration five can be seen in Table 22, Table 23, and Figure 24.

Table 22. Travel Time Impedance Values for Iteration Five

Obstructions	Barrier
Width Issues	Barrier
Surface Issues	3 seconds
Slope Issues	3 seconds

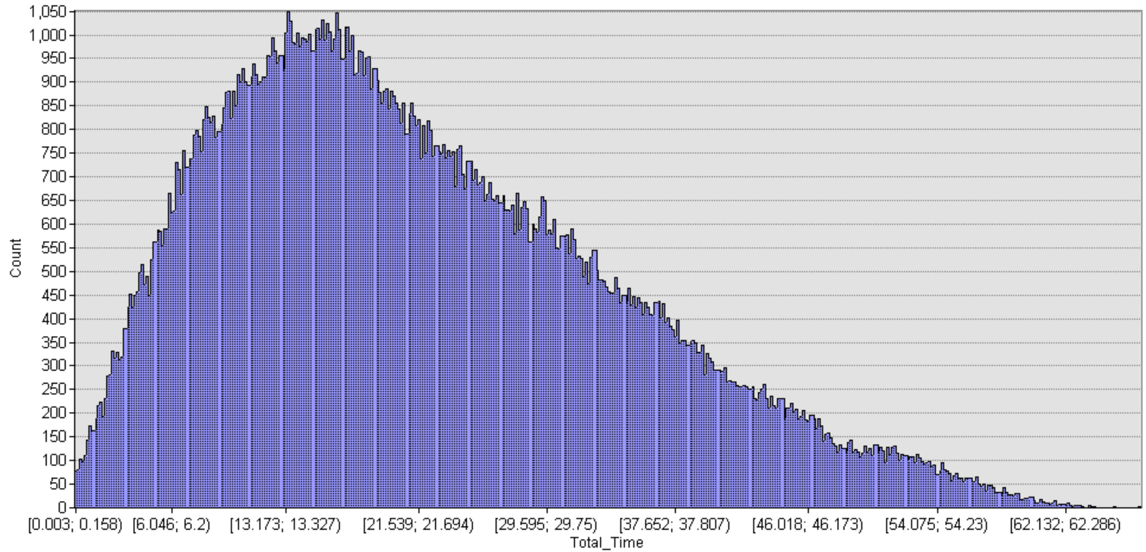

Figure 24. Frequency Distribution of Travel Time for Iteration Five

Table 23. Network Analyst Results for Iteration Five

Trip Attribute	Value
Number of Trips Completed	187,465 trips
Total Travel Time	4,095,714 minutes
Average Trip Travel Time	21.84 minutes
Maximum Travel Time	66.90 minutes
Total Length Traveled	818,057,759 feet
Average Trip Length	4363 feet
Trips Unable to be Made	62,535 trips

For iteration five, 62,535 trips were unable to be completed. These trips had either origins or destinations on parts of the network that had width issues, obstructions present, or did not have usable sidewalks present.

5.7 Discussion of Results

Lack of sidewalks and other pedestrian infrastructure compliance issues increase the average travel time, increase the average length of travel, and eliminate the number of possible trips that can be made by a wheelchair user. While the frequency of each pedestrian infrastructure compliance issue plays a large role in the total travel time impedance in each scenario, conclusions can still be made from the analysis. Compared to the base condition, the average travel time and average trip length increased for each of the five iterations. Along with this, the number of possible trips decreased from the ideal 250,000 trips in each of the iterations. The application of time-based impedance factors to the sidewalk links, designed to represent the extra time required by wheelchair users to navigate through sidewalk defects, results in longer travel times for all trips that involve defective sidewalk links. When travel time increases significantly along the original shortest path, the shortest path algorithms will route wheelchair travelers along new routes. These new routes are more circuitous than the original routes, as travelers take longer routes to avoid the travel time delays associated with defects on the network. As these paths change, the distance of these trips also increases.

This analysis shows that slope issues (iteration two) increase the average travel time and average trip length the most as compared to the other iterations, as seen in Figure 25 and Figure 26. The average travel time increased by 29.9% between the base condition and iteration two while the total number of possible trips decreased by 16.4%. The average trip length increased by 9.6%.

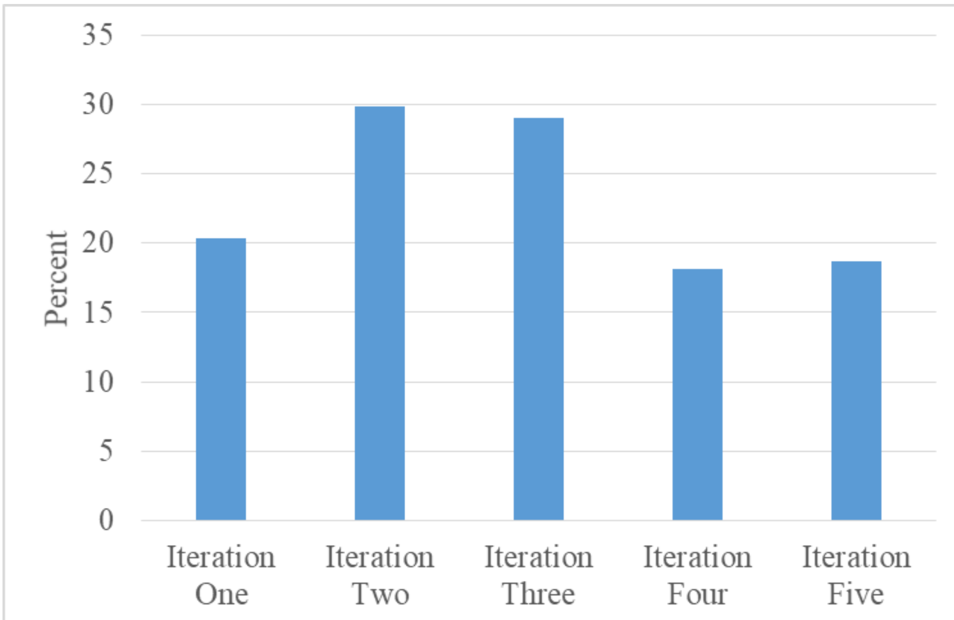

Figure 25. Percent Increase in Average Travel Time

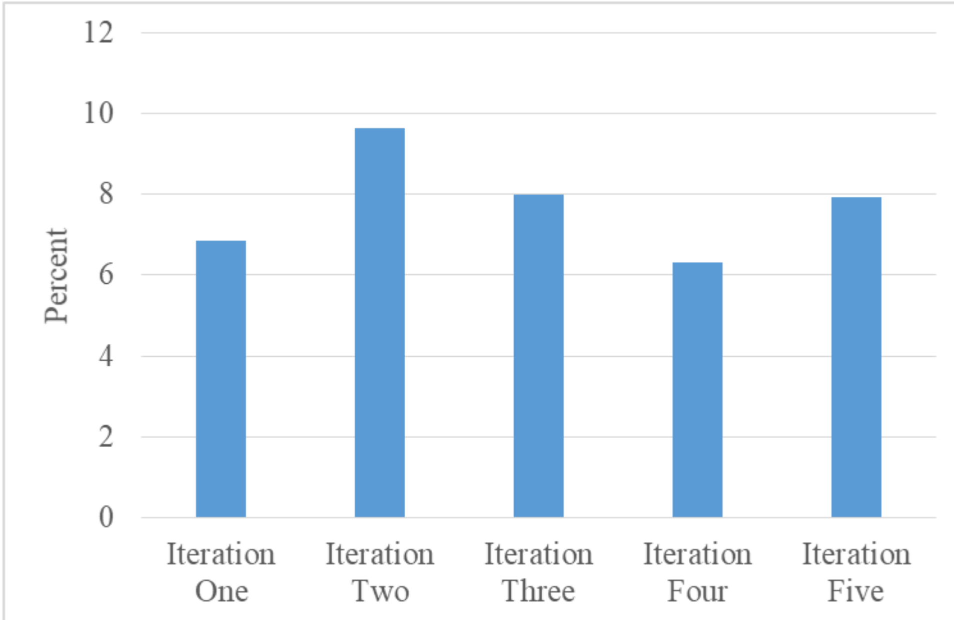

Figure 26. Percent Increase in Average Trip Length

Iteration five, where sidewalk width compliance issues and obstructions were assigned as network barriers, had the largest decrease in the number of possible trips. Obstructions, in particular, are a severe problem on sidewalk networks. Any permanent object that could cause a mobility impaired user to turn around, move into the roadway, possibly fall, or put them in any other form of danger should be avoided at all costs. Width issues were coupled in with obstructions because they can potentially have the same effects on wheelchair users. If a wheelchair or mobility aid is unable to fit at any point along the network due to width constraints, users are forced to either turn around or perform a dangerous maneuver. When dangerous ADA compliance issues such as these were treated as restrictions, the number of possible trips diminished by 25%. A comparison of all iterations can be seen in Table 24.

Table 24. Comparative Results of Iterations Zero through Five

Trip Attribute	Iteration Zero	Iteration One	Iteration Two	Iteration Three	Iteration Four	Iteration Five
Num. of Trips Completed	250,000 trips	208,779 trips	208,779 trips	208,779 trips	208,779 trips	187,465 trips
Total Travel Time	4,593,616 minutes	4,615,560 minutes	4,982,375 minutes	4,947,363 minutes	4,527,905 minutes	4,095,714 minutes
Average Trip Travel Time	18.37 minutes	22.11 minutes	23.86 minutes	23.70 minutes	21.70 minutes	21.84 minutes
Maximum Travel Time	56.01 minutes	68.00 minutes	74.05 minutes	72.10 minutes	66.90 minutes	66.90 minutes
Total Length Traveled	$10.1*10^8$ feet	$9.01*10^8$ feet	$9.25*10^8$ feet	$9.11*10^8$ feet	$8.97*10^8$ feet	$8.18*10^8$ feet
Average Trip Length	4042.8 feet	4319.6 feet	4431.6 feet	4365.0 feet	4297.6 feet	4363.0 feet
Trips Unable to be Made	0 trips	41,221 trips	41,221 trips	41,221 trips	41,221 trips	62,535 trips

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Travel time impedence values were added to pedestrian infrastructure issues located on Midtown, Atlanta's sidewalk network. The analysis calculated the total travel time resulting from the addition of impedance values for five hundred random origins and destinations throughout the network. Five different iterations of travel time impedance values were analyzed and compared to a base condition. The base condition represents the time it would take an able-bodied user to travel from origin to destination (with no added travel time from pedestrian infrastructure issues). The five iterations represented how different sidewalk design issues effect the travel cost for disabled users.

Adding travel time impedance values to the sidewalk network in Midtown increases the average travel time for walking trips (due to the increased time to traverse the network) and increased the average length of trips (due to changes in route away from the shortest path which increased both travel distance and travel time). When sidewalk segments that do not conform to ADA design guidelines were coded as impassible, for example when sidewalk obstructions or width issues prevent the passage of wheelchairs, the number of destinations that can be reached decreased significantly. These findings are important when taking into consideration the mobility of disabled persons and wheelchair users.

Many people are dependent on mobility aids. Adding travel time or physical stress associated with moving along sidewalks has the potential to deter people with physical limitations from traveling in the first place. This point is especially problematic, considering the fact that a large percentage of disabled individuals are unable to operate a vehicle on their own. These individuals have to rely on public transit or other people to meet their travel needs. If the sidewalk network that leads from an individual's home to a bus stop or transit station does not meet ADA standards, this further limits the mobility of the disability community and prevents individuals from accessing their only affordable transportation option.

While Midtown is considered one of the most walkable neighborhoods in Atlanta, this may only be true for able-bodied individuals. After coding missing sidewalks and sidewalks under construction as impassible in network analyst, and analyzing 250,000 random origin-destination pairs within the zone, the user of a wheelchair or mobility aid would not be able to complete about 25% of these trips. This situation will likely improve significantly when current high-rise construction in Midtown is completed over the next few years.

Present-day walkability measurements, such as Walk Score, are a good base assessment, but do not take into consideration all elements of pedestrian infrastructure. The Walk Score methodology considers the number of amenities within a distance to a location using the travel times associated with places between 0.25 and 1.50 miles. However, these distances and travel times could vary greatly for wheelchair users when taking into consideration the condition of the sidewalk infrastructure. A more accurate assessment of the walking environment should take into consideration the accessibility of a location, and the mobility factors associated with the routes from origin to destination. A person with a disability could potentially be misled by the Walk Score of their community, due to the fact that the score does not take into consideration ADA compliance issues.

As explored earlier, walking is good for public health, the environment, and the economy. These benefits should apply to people of all abilities, not just able-bodied individuals. People with physical limitations should be able to access goods and services, as well as walk or roll as a form of recreation, in an equitable manner. While the ADA has set pedestrian infrastructure standards to protect disabled individuals, legal cases indicate that cities and municipalities are not always adequately enforcing these standards. The process of sidewalk improvement through litigation is not a productive way to solve infrastructure problems. Sidewalk asset management systems that are designed to inventory sidewalks and track conditions can help cities to properly maintain sidewalks and prioritize sidewalk repairs. While funding is limited, communities can use sidewalk databases to identify severe conditions of ADA design noncompliance that prevent sidewalk travel, add travel time, and/or add travel length for people with disabilities. From there, communities can prioritize which problems to fix (and fix first) to improve mobility and create an equitable space for residents with physical limitations.

Probably the first order of business is to repair or install sidewalks in locations where desired destinations are currently inaccessible by sidewalk. If sidewalks are under construction, alternative pathways and building access should be provided as a condition for construction approval. The disability community should be alerted of any construction restrictions via public signage and community newsletters. Cities and municipalities should actively plan for the support of disabled individuals who live or work in areas affected by construction. Constructing sidewalks that help complete the sidewalk network is vital in ensuring that persons of all abilities can at least successfully make the same number of trips as able-bodied individuals.

It is also important to repair sidewalk and ramp width issues and obstructions as soon as possible, given that these elements prevent wheelchair passage. After addressing impassible sidewalk sections, addressing travel time impedance (additional time and effort to navigate a design or condition issue) will still need to be wheelchair users. Policy analysts can then develop sidewalk repair prioritization systems based upon the prevalence of each issue causing travel time impedance, how each issue effects mode choice, and the total travel time added by each issue.

The travel-time analysis provides insight on mobility issues associated with pedestrian infrastructure compliance issues. The ease of movement for disabled individuals can be significantly different than that of able bodied individuals when taking into consideration ADA design compliance issues along sidewalk networks. The mere presence of sidewalks does not imply that a disabled individual can equitably access goods, services, and affordable public transportation options. Instead, the condition of the sidewalk network can impede access to goods and services or increase the time and length it takes to reach a certain destination. To accurately assess mobility for disabled individuals, sidewalk problems with assigned travel time impedances should be implemented into routing services such as Google Maps and Waze. By adding sidewalk compliance issues into routing services, disabled individuals could have a more accurate representation of the time, length, or difficulty of their trips.

Sidewalk networks should also be added into travel demand models to better assess walk trip generation (which may be limited if the sidewalk infrastructure is lacking or does not meet ADA design standards). Developing independent sidewalk networks and tracking compliance with associated ADA design standards can improve the prediction of users' movements throughout transportation networks. Adding pedestrian infrastructure into travel demand models will improve the modeling of pedestrian behavior for a variety of purposes. The quality and presence of sidewalks drives mode choice in dense urban areas that have many amenities within walking distance. However, without accurate sidewalk connectivity and condition data, it is difficult to predict pedestrian movement. Once a separate pedestrian network is in the model, and sidewalk quality issues that affect walking behavior are integrated as model input data, new algorithms can be developed to better-predict pedestrian trip generation, destination choice, and mode choice. While this travel time analysis focused on the amount of time added to disabled users' trips, it also provides insight on the potential travel behavior of disabled users. Sidewalk compliance issues ultimately effect users' mode choice decisions. If the sidewalk network contains issues that cause great strain to a disabled user, they are less likely choose 'walking' as their mode of transportation. Added travel time alone may not be enough to assess the impact of sidewalk condition on mode choice. If sidewalk travel is more arduous for disabled users, this may also affect travel decisions. Thus, disabled individuals are less likely to choose walking as a form of transportation because of the quality of the associated pedestrian infrastructure.

CHAPTER 7. LIMITATIONS AND FUTURE RESEARCH

The major limitation in this analysis is the lack of survey data designed to obtain impedance information associated with sidewalk design and condition issues. Impedance factors were gleaned from the literature and incorporated into network analyst. However, proper incorporation of sidewalk circuity and condition impacts in an impedance analysis should come from a detailed stated preference survey of Atlanta wheelchair users. A potential survey may ask disabled persons to assign a travel time value to each pedestrian infrastructure problem collected by Sidewalk Sentry and Sidewalk Scout. Disabled individuals would also be asked to identify barriers that impede them from choosing walking as their primary mode choice. The survey would identify users with varying levels of physical ability, differentiating users who use canes, manual wheelchairs, or motorized wheelchairs. The expected result would be differing travel time impedance values for people with differing physical abilities. Travel time impedance values estimated from survey responses could be added to the pedestrian network for use in a transportation demand model.

The proposed incorporation of sidewalk networks (with associated travel time impedance values) to travel demand models is another potential limitation. The most advanced activity-based travel demand models, such as ABM15 for the Atlanta region, can take more than 24 hours to complete a modeling run, due to their data intensive nature. Adding more links and data to travel demand models will slow down the modeling process. Future research will need to assess the benefits and costs of incorporating sidewalk networks and impedance into these models.

Another limitation is that embedded travel decisions in real-world scenarios do not result in the shortest path of travel. Dijkstra's algorithm calculates the shortest path in a way that humans are not capable of. Because Dijkstra's algorithm calculates the shortest path from point to point along each OD pair, the total length of the path is shorter than what would be expected in the real world. The average travel time and average length travelled are most likely higher in real world conditions where humans are routing themselves from point A to B. The only instance where this would not be the case is if a disabled person already knew of the presence of missing sidewalks, obstructions, or sidewalk width issues that would cause them to turn around and reroute. Intersection delay, the grade of roadways, and pedestrian congested were three limitations of this analysis. The average travel time would most likely increase if these three measurements were taken into account.

Future research would consist of an extensive survey of disabled individuals to obtain perceived travel time impedance values for users of varying abilities. The Georgia Tech sidewalk research team plans to administer a travel time impedance survey within the Cobb County disability community in 2018. Once the impedance values from this survey are integrated into the Midtown network, a more accurate analysis of travel time and travel length can be calculated. Similar pedestrian infrastructure assessments should also be considered for cities across the United States. Sidewalk databases are rare, hence the inaccuracies when assessing the walking environment of neighborhoods using tools like Walk Score. However, if sidewalk infrastructure data can become commonplace, thanks to the availability of semi-automated and affordable data collection processes, the mobility limitations of pedestrian infrastructure can be better assessed.

Future research should also include the provision of locations of pedestrian infrastructure compliance issues and associated travel-time impedance values to routing companies such as Google and Waze. Incorporating sidewalk compliance issues into commonly used navigation applications can help in routing individuals with physical limitations. While an ideal world would consist of pedestrian infrastructure that meets ADA standards, this is not likely to occur for many years. To make pedestrian infrastructure more equitable in a timely manner, Google Maps and Waze should be encouraged to incorporate sidewalk data, along with a routing function specifically for disabled persons. This could be accomplished through a partnership between Georgia Tech, cities around the United States, disability activists, as well as large navigation-focused companies such as Google.

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